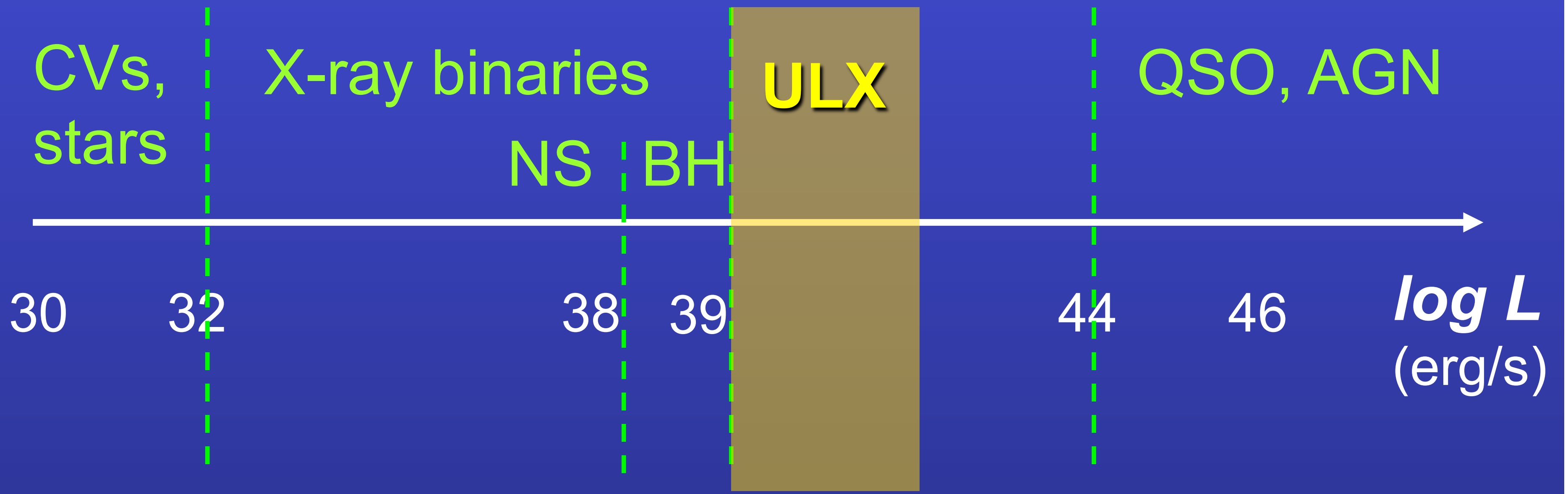
Ultraluminous X-ray sources

Accretion state or new class of sources?

Ultra-luminous X-ray sources



Mass of accreting object $\longrightarrow$ max luminosity

Eddington limit: $L = 1.3\times10^{38}\ (M/M_{\odot})$ erg/s

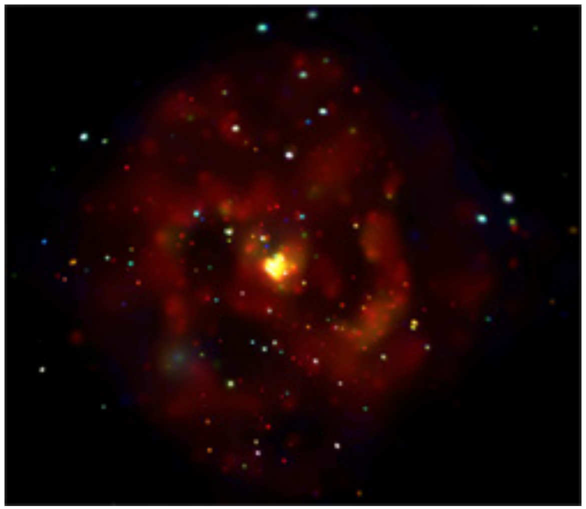
Flux $f \longrightarrow L = 4\pi d^2 f > 10^{39}$ erg/s: **ULX**

Ultraluminous X-ray sources: definition

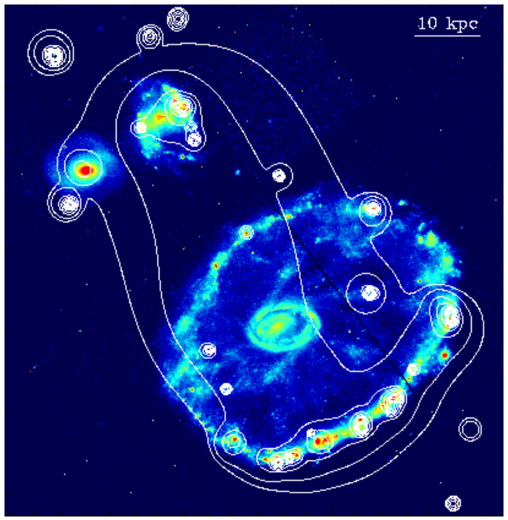
ULXs are point-like, off-nuclear X-ray sources in nearby galaxies with an X-ray luminosity >> L_{Edd} for 1 $M_{\odot}$ source (typically, >10^{39} erg/s)

ULXs are associated with both star-forming regions in spiral and irregular galaxies (large fraction), blue compact dwarf galaxies, and the old stellar population in elliptical galaxies

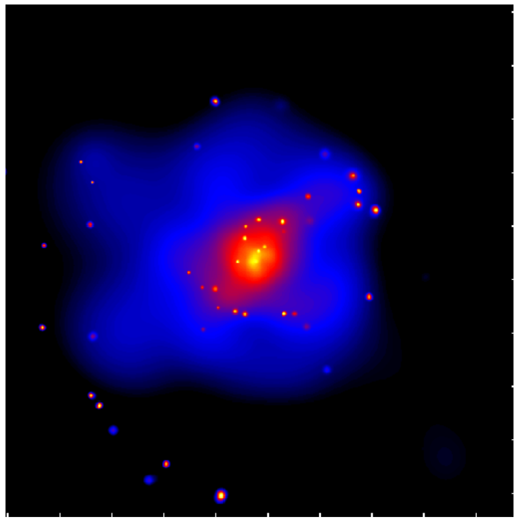
X-ray luminosity, variability and spectral transitions suggest objects in accretion
Most ULXs are persistent for years/decades. Higher variability for those in SFGs than in elliptical galaxies



Antennae galaxies:18/49 sources are classified as ULXs (Zezas+02)



Cartwheel galaxy system: >20 ULXs, 12 being in the outer SF ring (Gao+03)



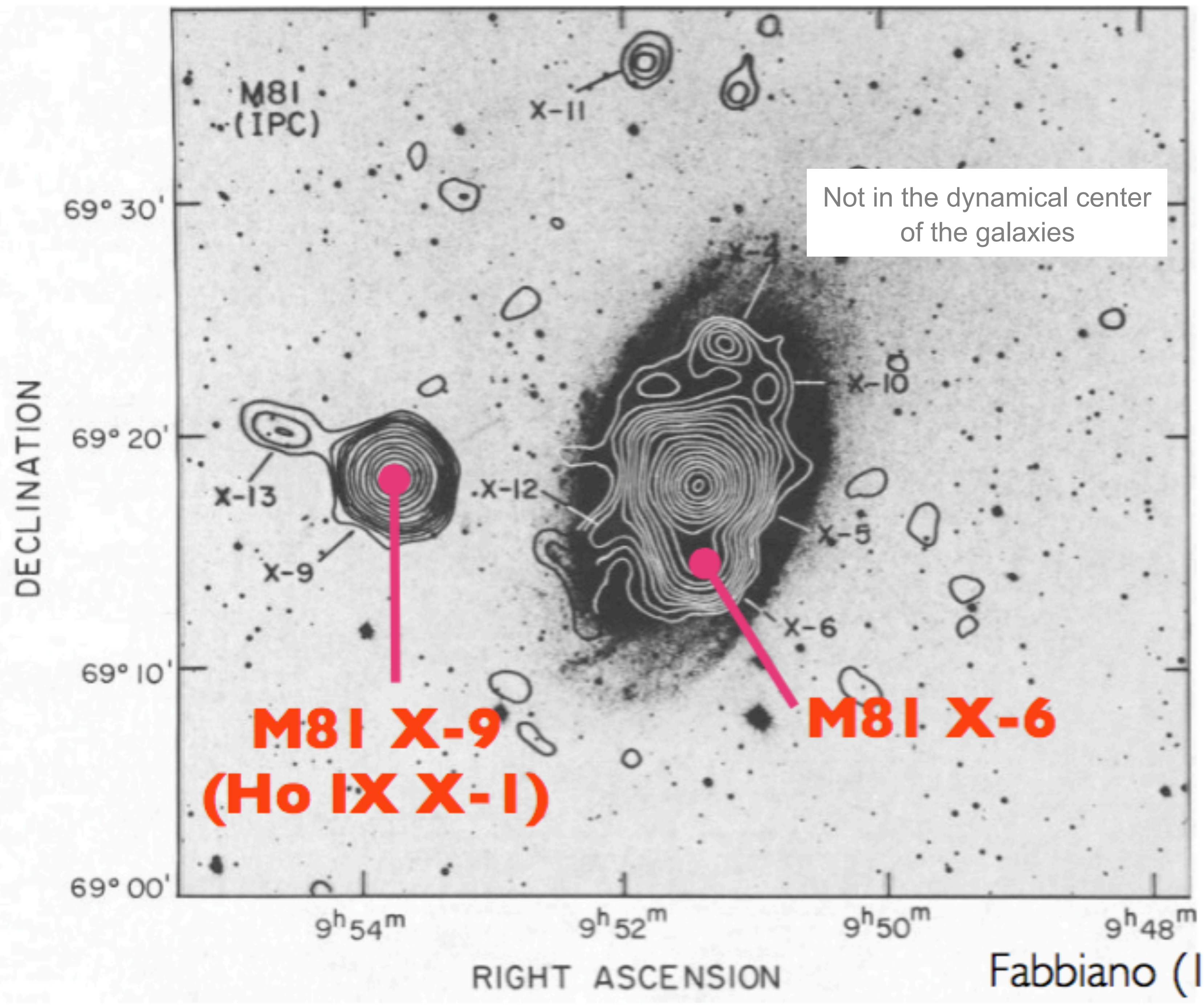
ULXs in an elliptical galaxy

Pre-*Chandra* and XMM era: *The Einstein* X-ray observatory

Luminous X-ray sources are not common objects, perhaps one in 10^9 stellar systems […]
It is useful to study these objects to improve statistical estimates, to better define the extremes of the phenomenon, to determine the dependence upon the stellar population and galactic morphology, and possibly to discover new classes of these rare objects

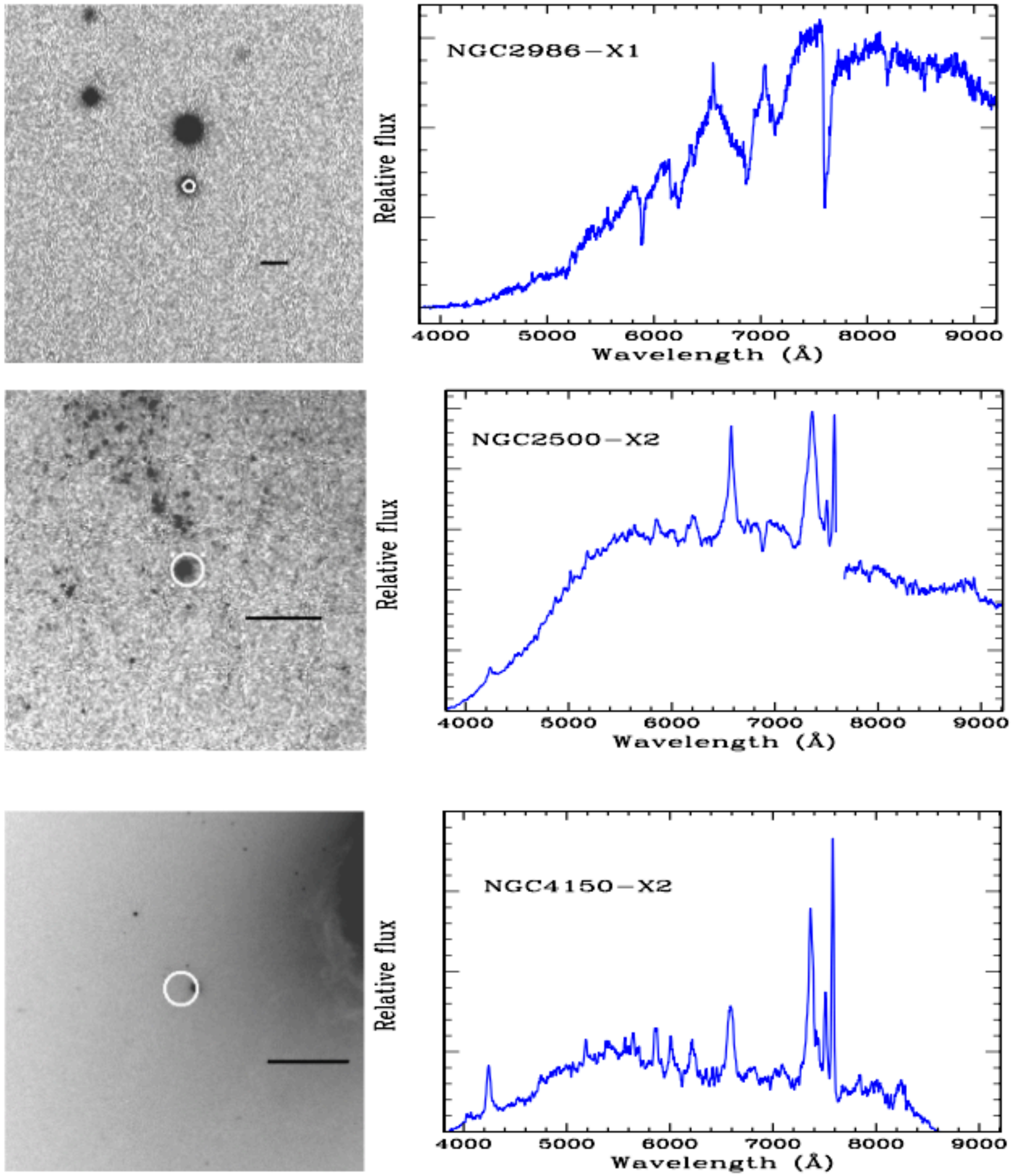
Long & Van Speybroeck (1983), *Accretion Driven X-ray Sources*

In X-ray surveys with limited follow up, (background) AGN can contaminate the number density of ULXs
Many miss-classification in literature



Fabbiano (1988)

“Misclassified” ULXs



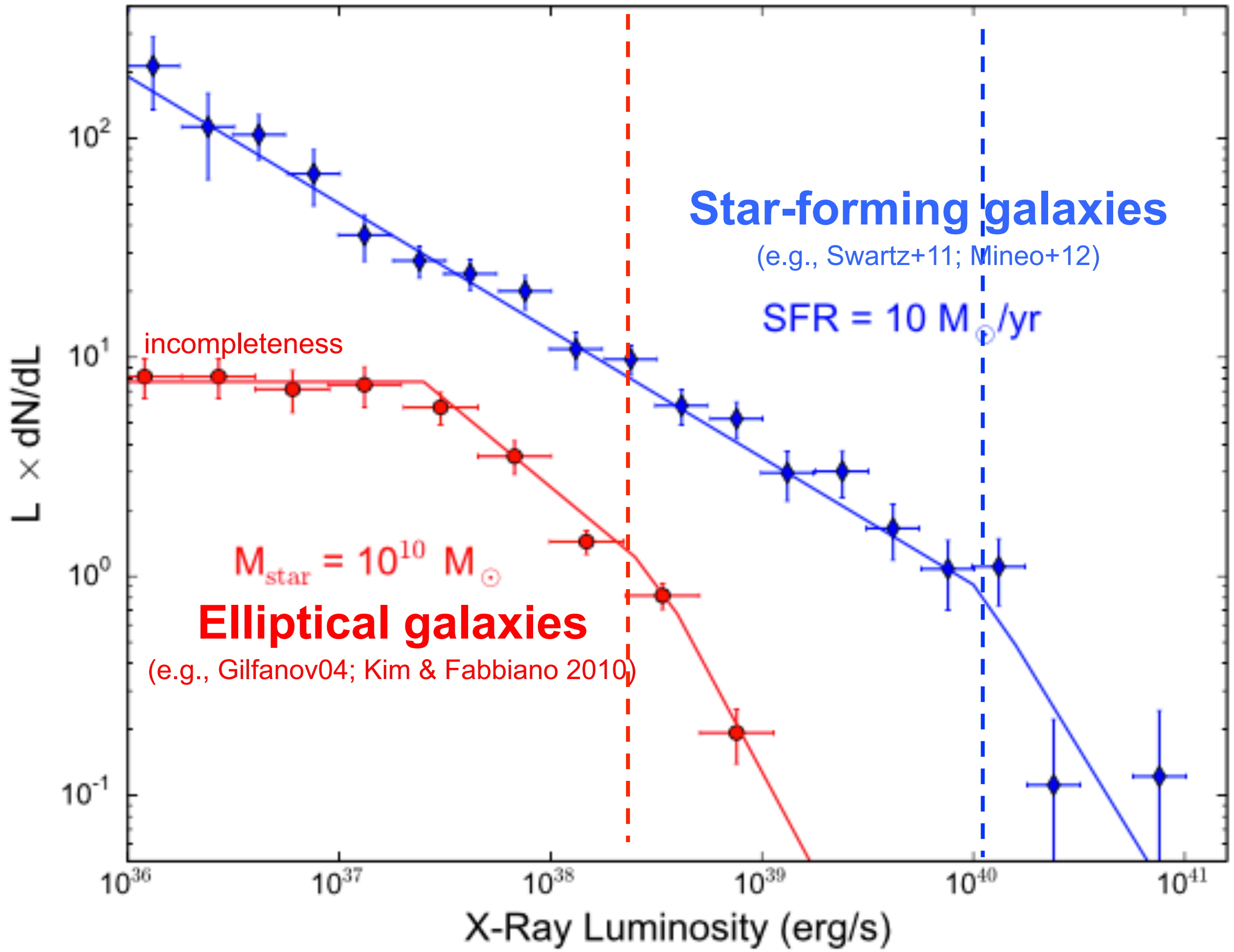
Foreground star

Background AGN

Background AGN

Gutierrez 2013

On the nature of ULXs: galaxy X-ray luminosity function



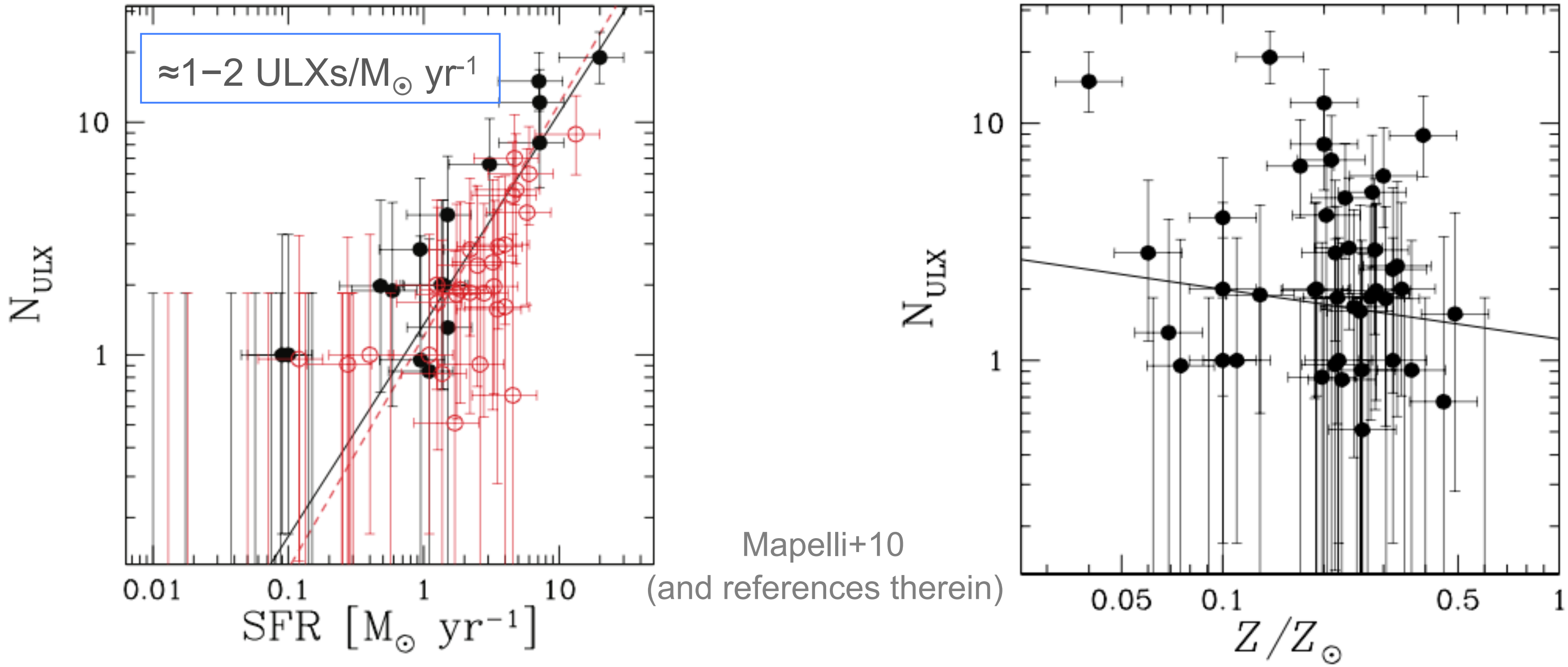
Kaaret+17, ARA&A review

XLF break at ≈(3−7)×10^{38} erg/s ➔ Eddington luminosity for NS, few BHs present?

XLF break at ≈(1−2)×10^{40} erg/s ➔ is the break related to an Eddington luminosity?

NS binaries expected to be ≈10−50 times more numerous than BHBs; up to the break, same population of standard XRBs (HMXBs)

ULXs vs. SFR and metallicity



Mapelli+10
(and references therein)

- Galaxies with $Z<0.2Z_\odot$
- Galaxies with $Z>0.2Z_\odot$

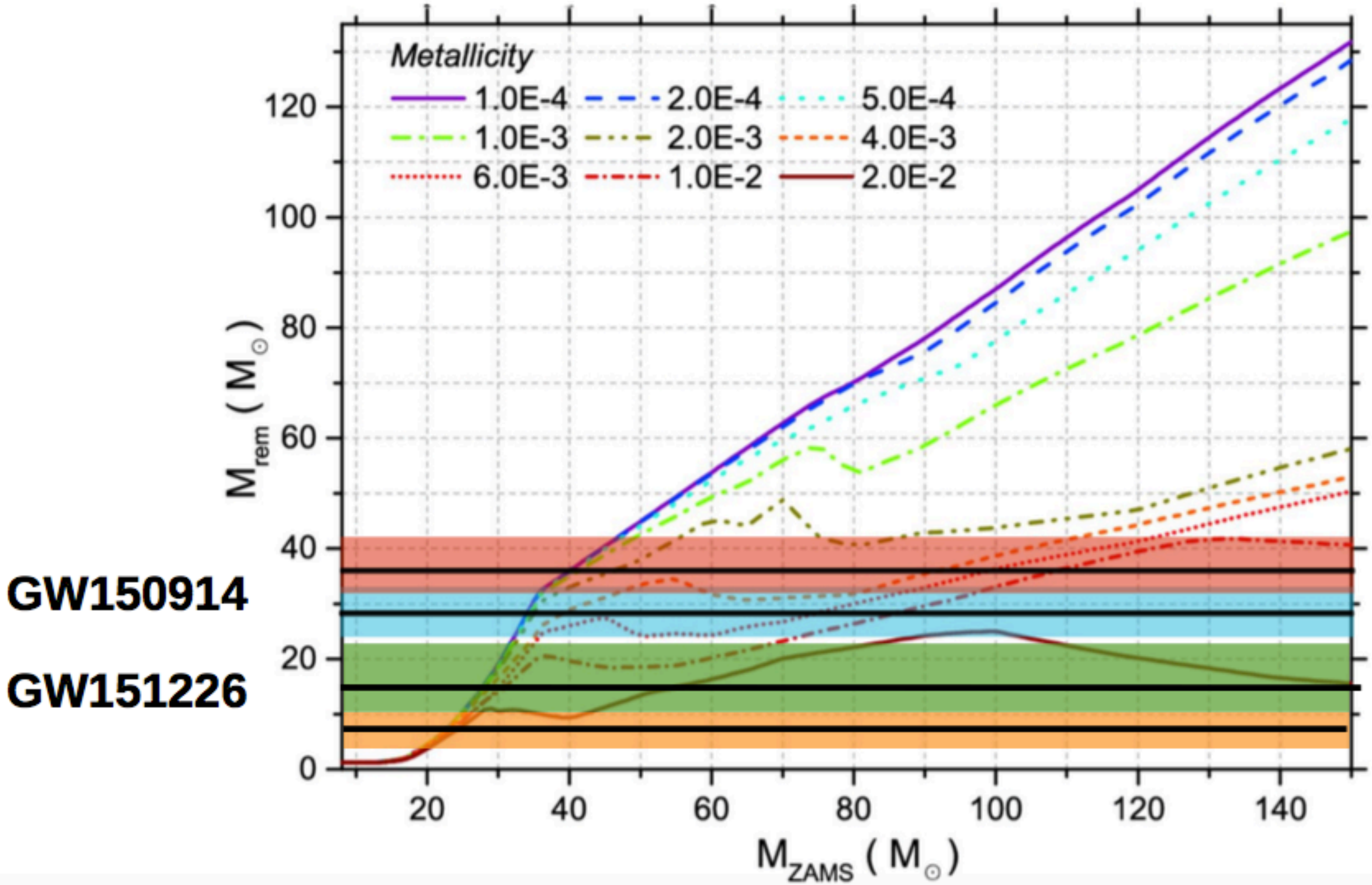
Lower metallicity enhances the formation of BHs
(influence of metallicity on the evolution of massive stars?)

IMF and fraction of binary systems is fundamental

Low-metallicity, massive ($\geq 40\ M_\odot$) stars lose only a small fraction of their mass due to stellar winds and can directly 'evolve' into massive BHs ($25\ M_\odot \leq M_{BH} \leq 80\ M_\odot$). These BHs can power most of the known ULXs without requiring super-Eddington accretion or anisotropic emission

Association of ULX with massive BH and GW?

DO MASSIVE BLACK HOLES EXIST? GW DETECTION!!!



PARSEC stellar evolution (Tang, Bressan+ 2014; Chen, Bressan+ 2015) **+ delayed SN model** (Fryer+ 2012)

From Mapelli

- ✓ Potentially, high energy output → ionizing photons

- ✓ Large number locally

- ✓ Preferentially associated with low-metallicity systems and in star-forming galaxies

- ✓ XLF fits in with predictions of X-ray binary formation in the early Universe

Role in the re-ionization process in the early Universe?

Outline of the lesson on ULXs

- ❑ ULX masses ➔ progenitors and formation
- ❑ Main unsolved issue: isotropic or beamed emission?
- ❑ X-ray spectral properties and spectral states
- ❑ Outflows
- ❑ ULX bubbles
- ❑ Optical counterparts
- ❑ Transient ULXs
- ❑ Eclipses in ULX

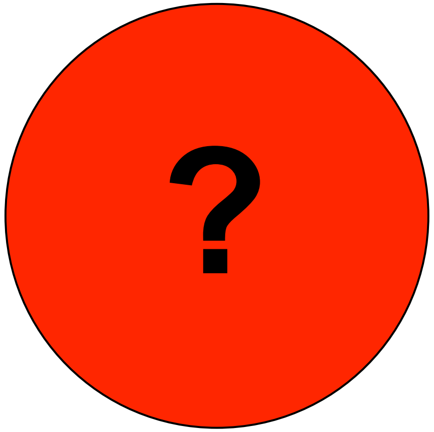
ULX: masses and progenitors. I

NS

Stellar-mass BH

Massive stellar BH

IMBHs ($\approx 10^2 - 10^5$ $M_\odot$)



$L_X > 10^{39}$ erg/s implies > 10 $M_\odot$ for Eddington-limit emission

(if no beaming is present)

ULX: masses and progenitors. II

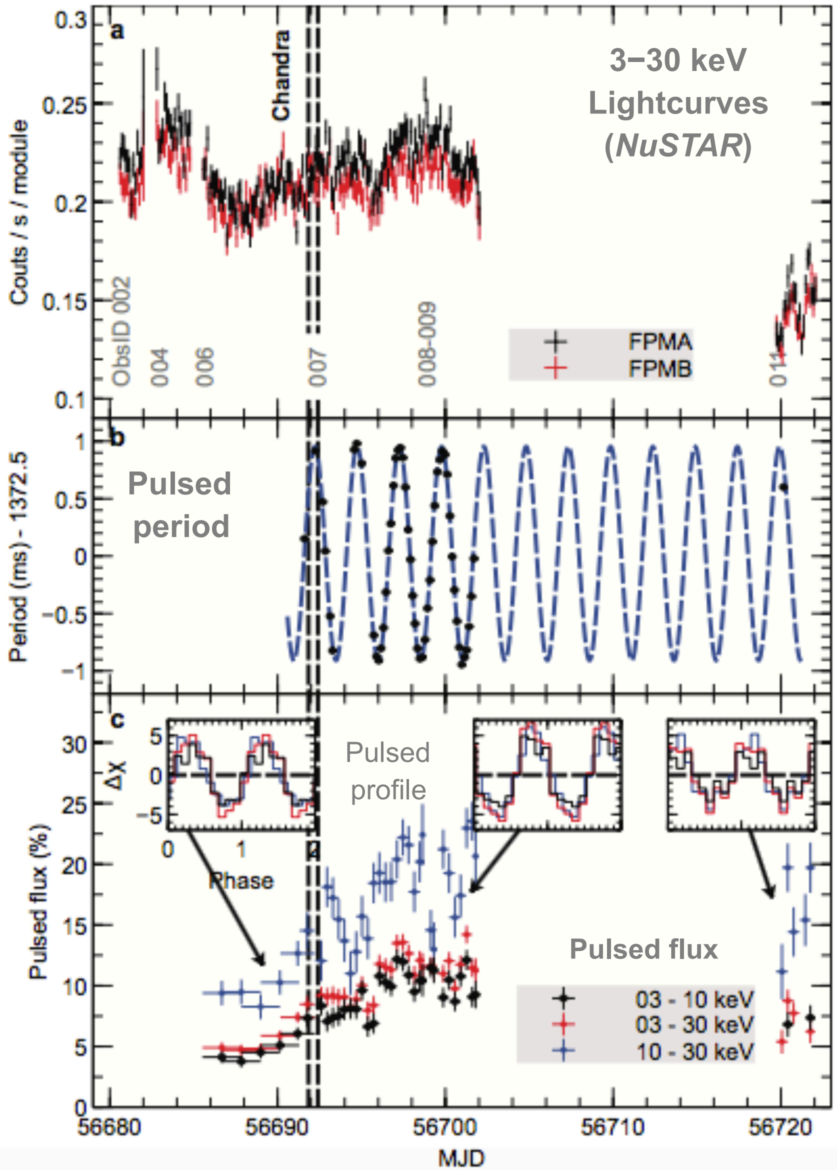
Direct mass measurements remain elusive

- ❑ Optical counterparts usually very faint (mag>21; e.g., Roberts+08)
- ❑ Not easy to identify disc emission lines, stellar absorption lines
- ❑ "Contamination" of optical spectra by outflows

Current situation **MIXED BAG**

- ➢ Most ULXs can be explained as stellar-mass BHs
- ➢ Few are clearly NSs (because of the associated pulsar emission)
- ➢ IMBHs are a few and likely represent an exception

ULX powered by an accreting NS. I



Bachetti+14, Nature

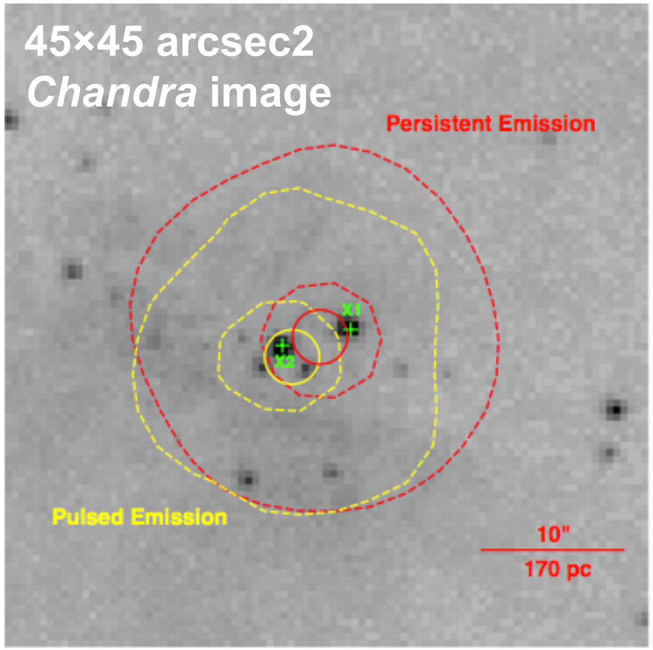
Bright ULXs in M82 (5" sep.)

Pulsations of P=1.37s, 2.5-day sinusoidal modulation

➔Pulsation from rotation of a magnetized NS

➔Modulation from the binary orbit

$L_X \approx 10^{40}$ erg/s, $100 x L_{Edd}$ (high-L_X: Roche lobe overflow most likely)



ULX powered by an accreting NS. II

NuSTAR
2−30 keV band

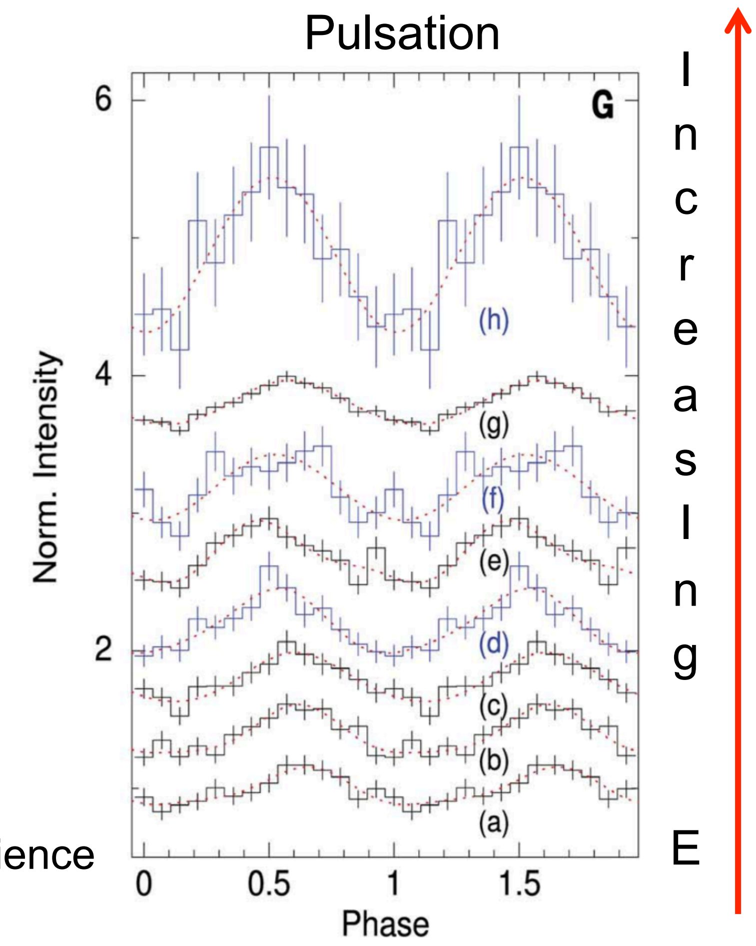
NGC 5907

Spin period=1.43s (2003) − 1.13s (2014) → spun-up

L_X≈10^{42} erg/s, 1000xL_{Edd} (high-L_X: Roche lobe overflow most likely)

P_{orb}≈5.2 days

If B too high, propeller effect would strongly limit the accretion



Israel+17, Science

see also Misra et al. (2020) and King & Lasota (2020)

NS highly present in nature, likely more important than previously thought among ULXs

ULX: masses and progenitors. III. The case of IMBHs

- Merging of stars in a young stellar cluster followed by direct collapse into an IMBH (Portegies Zwart et al. 1999) – see the case of ESO 243-49 HLX-1

- Merging of binaries that have a BH with initial mass of ~50 $M_\odot$ in a globular cluster (Miller & Hamilton 2002)

- Evolution of primordial population III stars (Madau & Rees 2001)

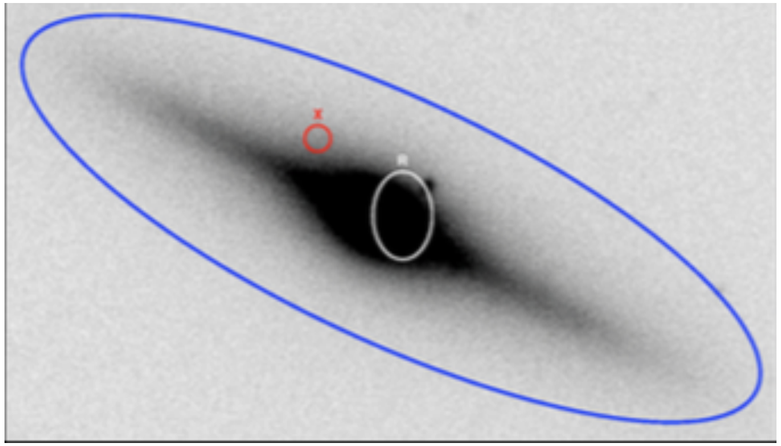
BINARY FORMATION

- Exchange encounters (Kalogera et al. 2004)

- Tidal capture (Hopman, Portegies Zwart, Alexander 2004)

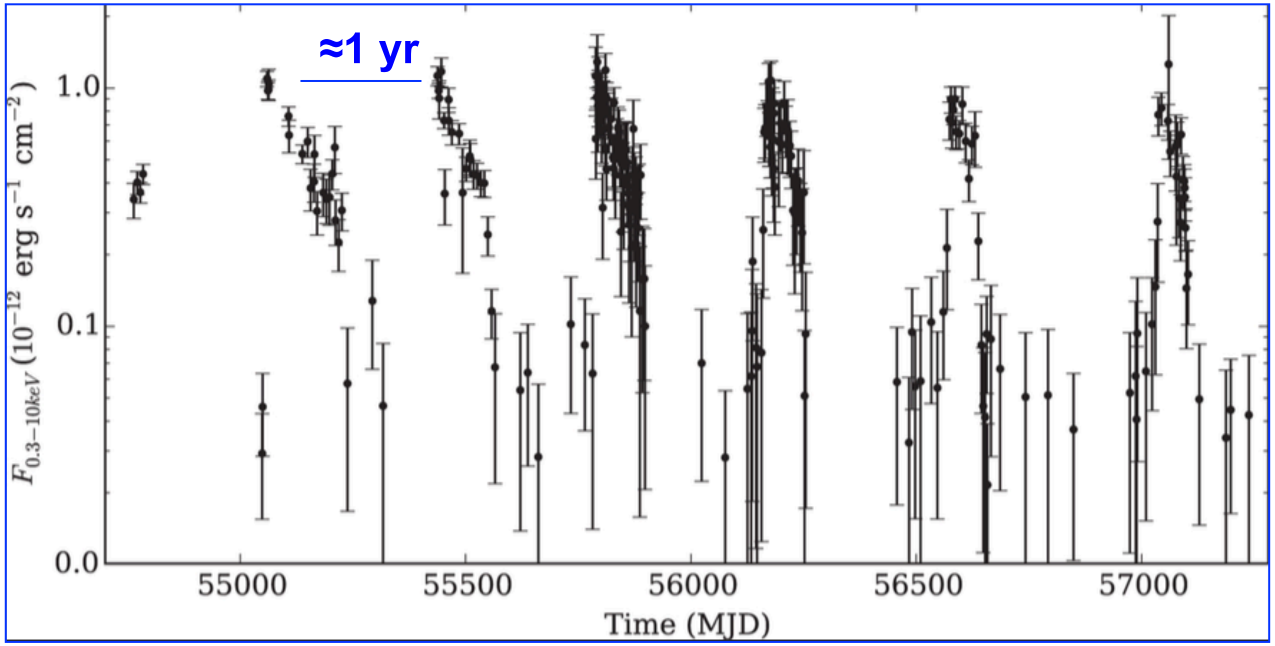
An IMBH candidate: HLX-1

ESO 243-49



- Peak X-ray luminosity $\approx 10^{42}$ erg/s
- Radio flares
- Low/hard X-ray transitions

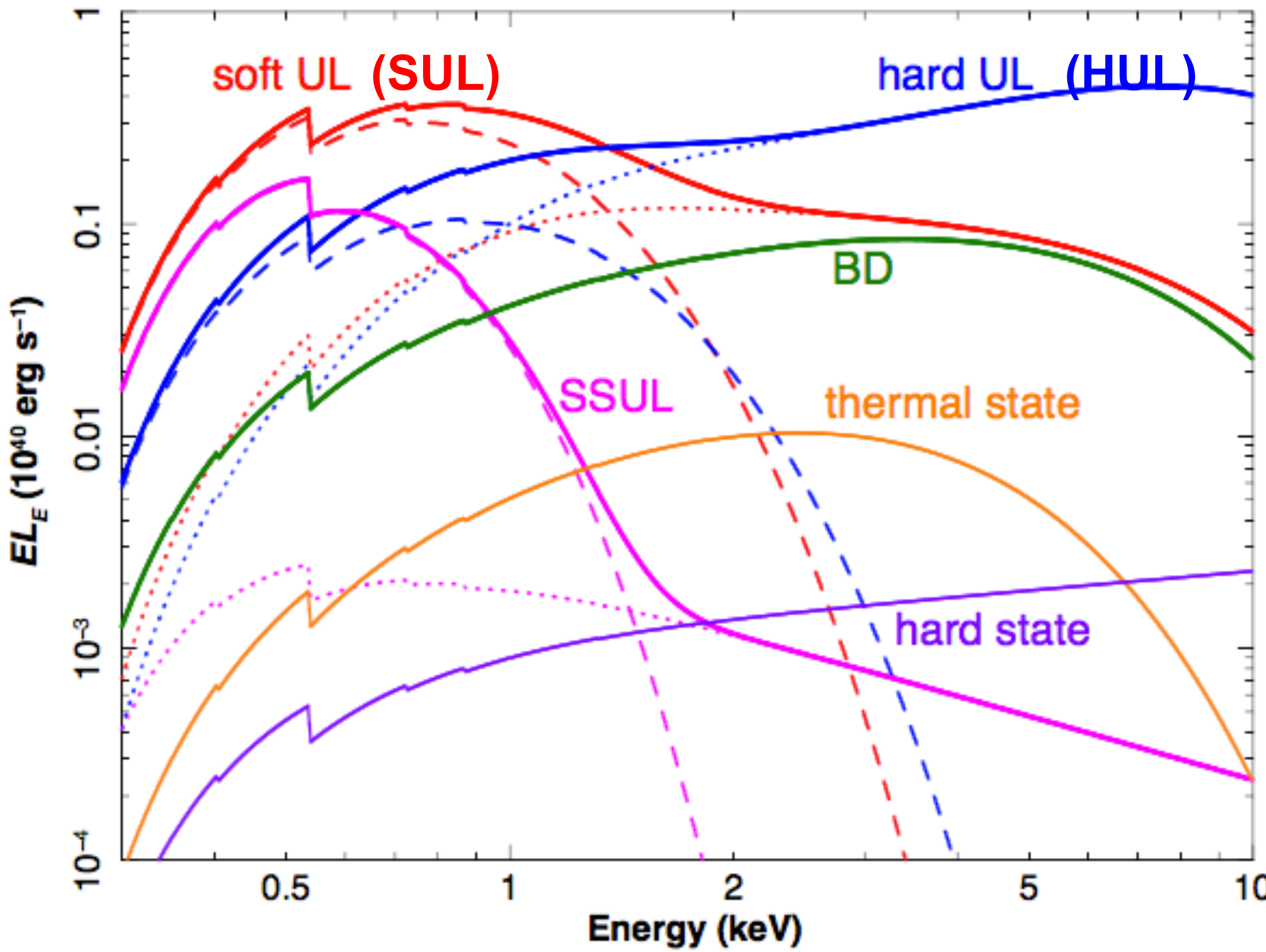
➔ $M_{BH} \approx 500-1000\ M_{\odot}$?



IMBHs among ULXs likely present but in low number

X-RAY SPECTRAL PROPERTIES (AND STATES) OF ULXS

X-ray spectral states. I



UL: ultraluminous (**SUL**, **HUL**)

BD: broadened disk

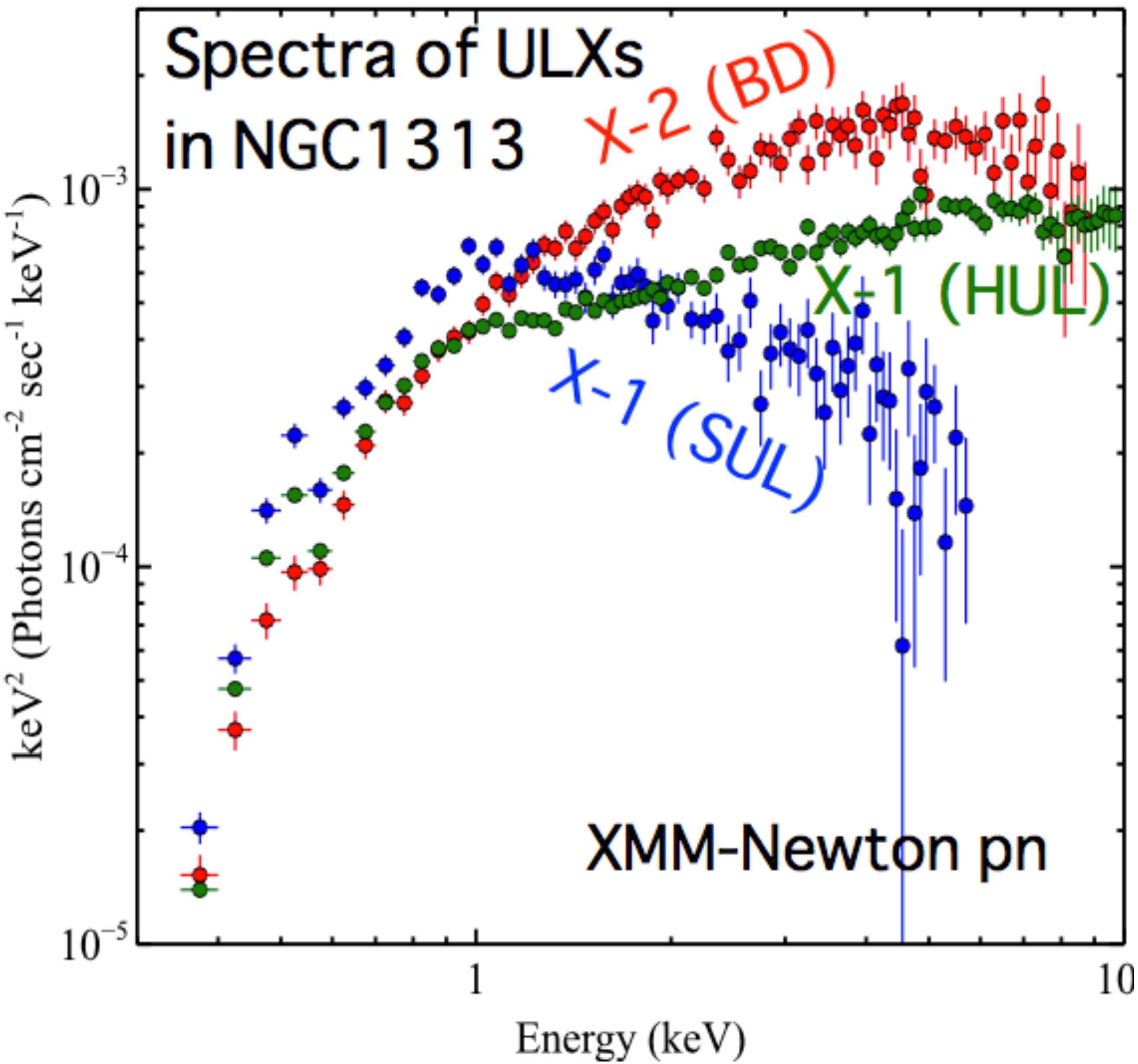
SSUL: supersoft ultraluminous

- More than 1 component
- Cool discs
- Except for BD, the disc dominates only up to 2 keV

Other curves: GBHBs (kT_e~100 keV, τ≤1)

UL: either soft or hard, depending on the peak in the SED. kT_{disk}≈0.1−0.3 keV; kT_{corona}≈1.5−3 keV, τ>6
BD: broadened disk emission, i.e., p-free disk model ($T \propto r^{-p}$ with $0.5 < p < 0.75$); MCD: p=0.75. $kT_{disk, inn}$≈1−2.5 keV, p~0.6
SSUL: cool BB component producing most of the X-ray flux. kT_{disk}≈0.1 keV; steep (Γ=2−4) powerlaw

X-ray spectral states. II

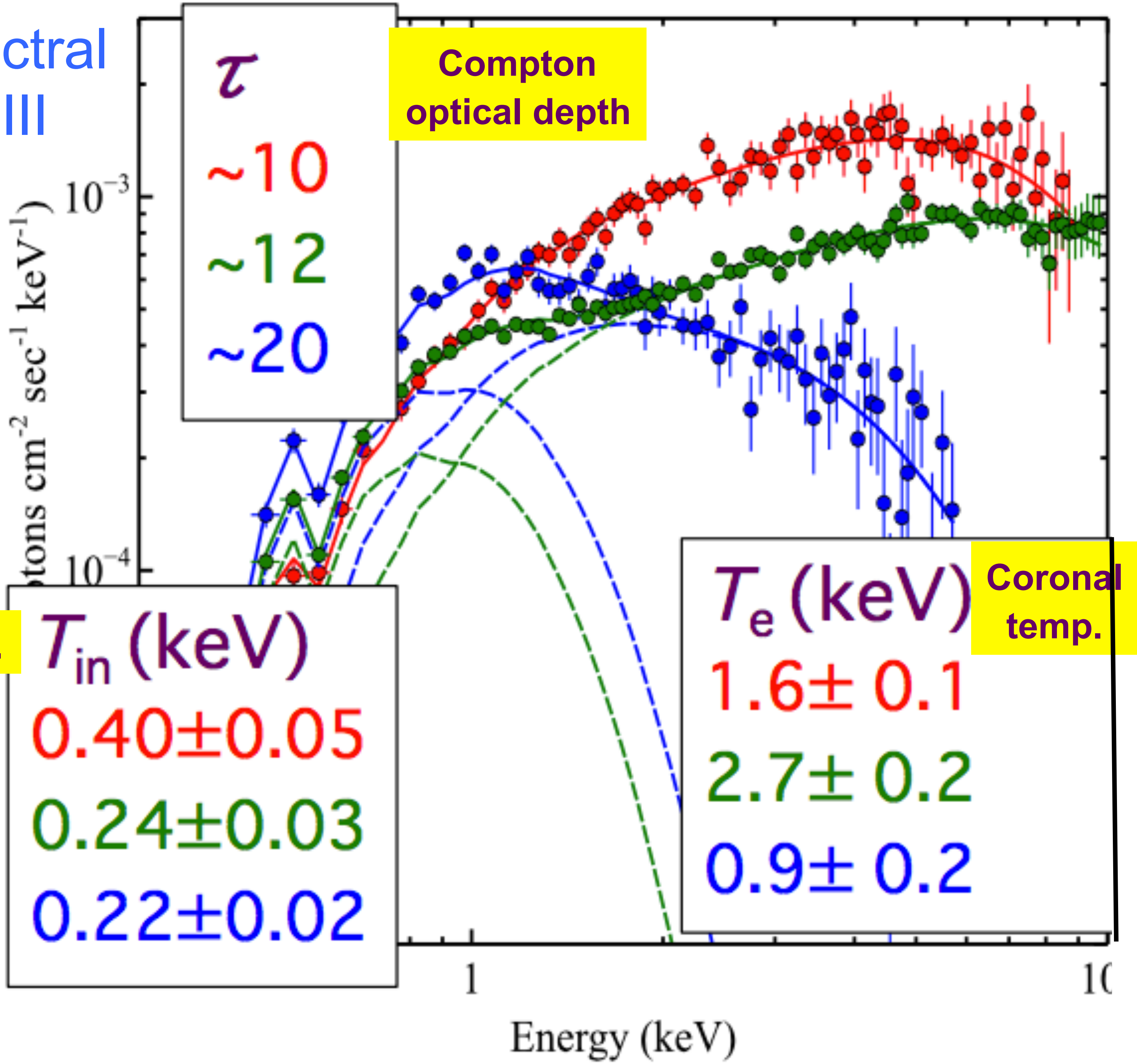


spectral changes on month-year timescale

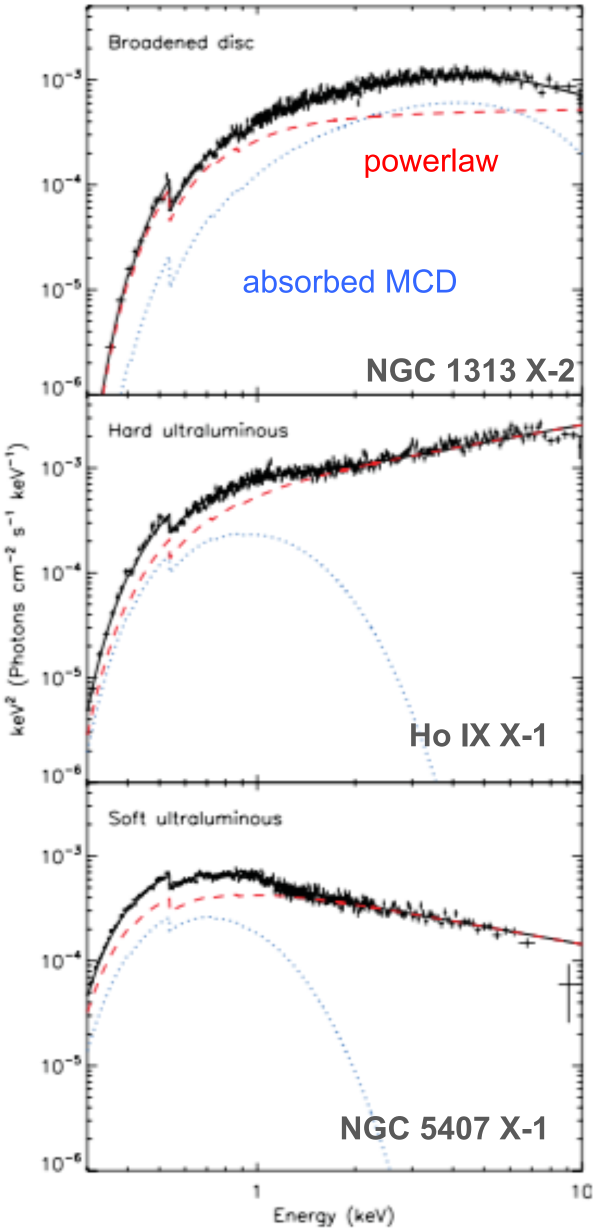
X-ray spectral states. III

Inner AD shrouded by an opt. thick corona, leaving only the outer regions to be observed as soft excess

Inner disk temp.



Properties of three ULX regimes

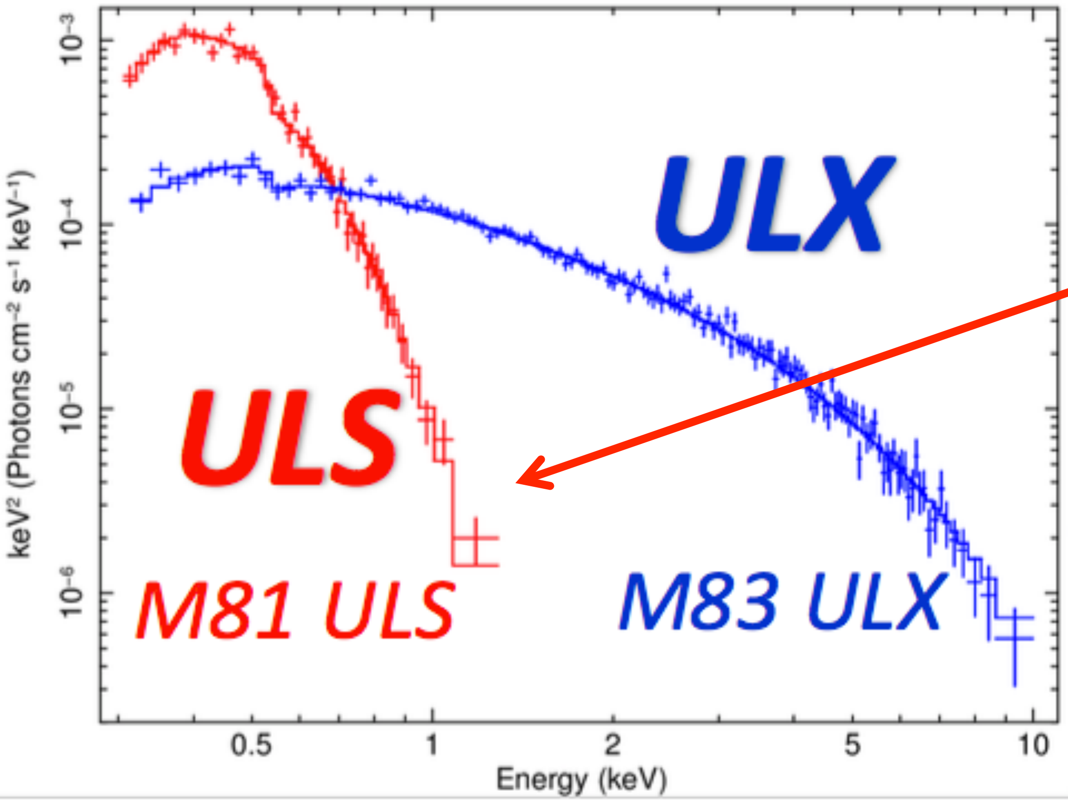


Broadened disk: slim disk, $L \approx L_{Edd} \lesssim 3 \times 10^{39}$ erg/s

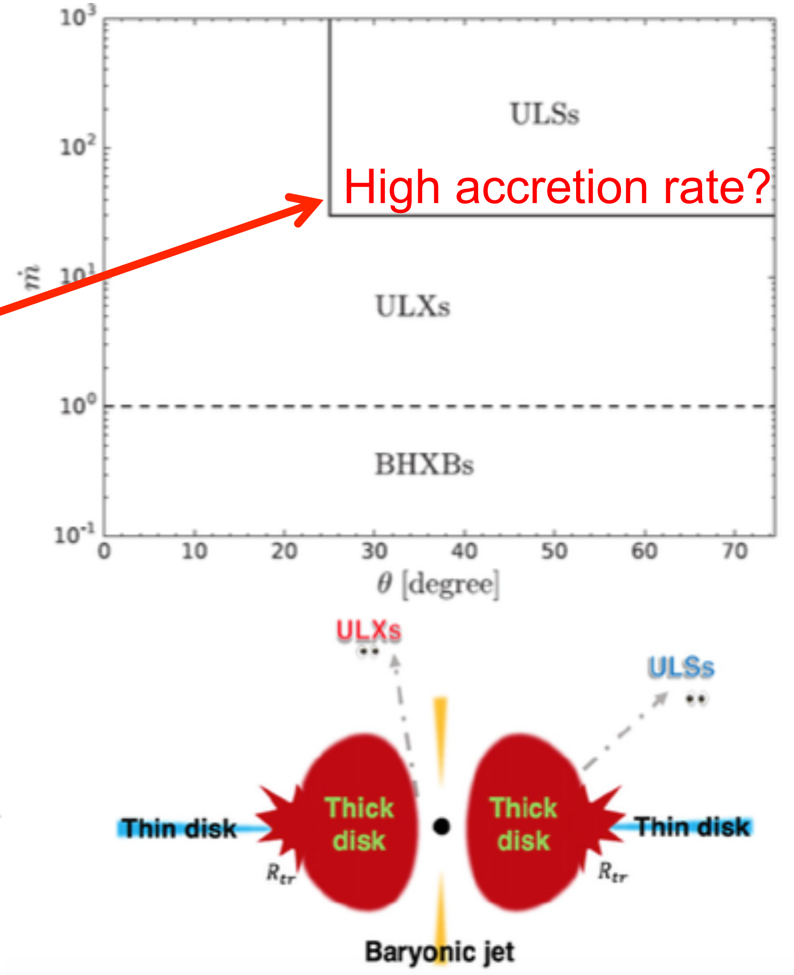
Hard ultraluminous: $L > L_{Edd} \gtrsim 3 \times 10^{39}$ erg/s, low inclination (more face-on)

Soft ultraluminous: $L > L_{Edd} \gtrsim 3 \times 10^{39}$ erg/s, high inclination (more edge-on)

Sutton+13

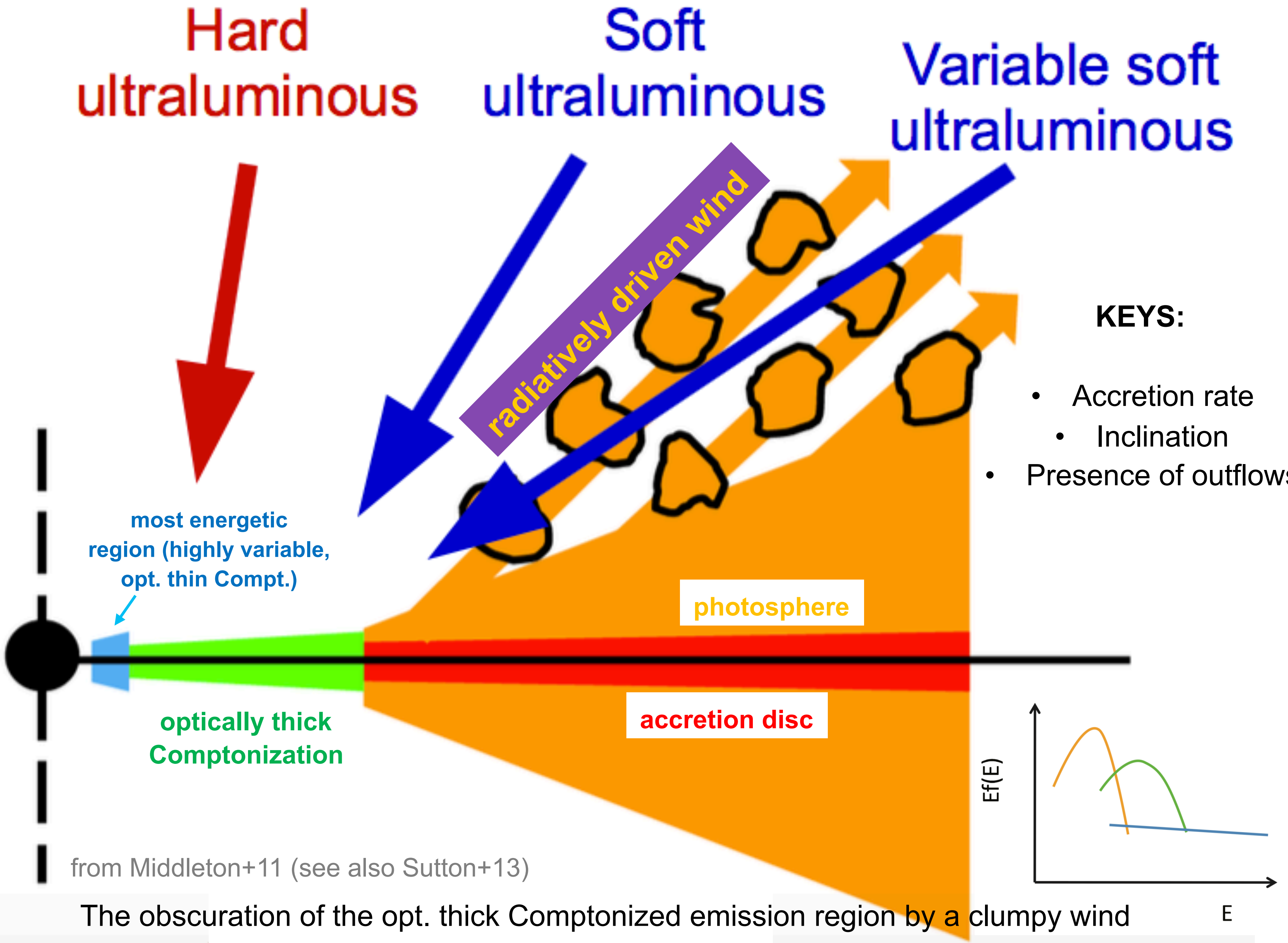


ULX
ULS
M81 ULS
M83 ULX
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
Energy (keV)



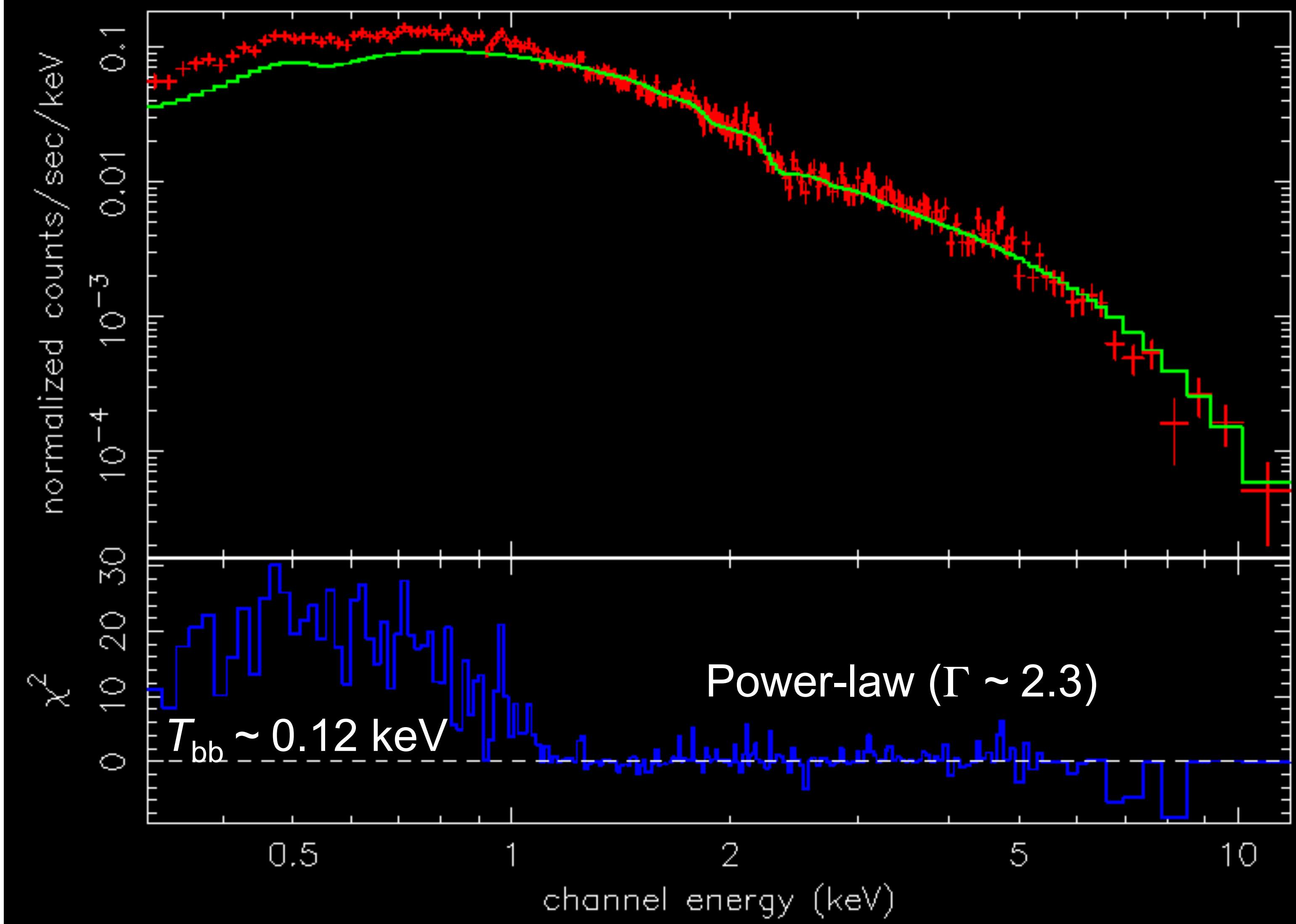
ULSs
High accretion rate?
ULXs
BHXBs
θ [degree]
ULXs
ULSs
Thick disk
Thick disk
Thin disk
Thin disk
Baryonic jet

ULS=SSUL

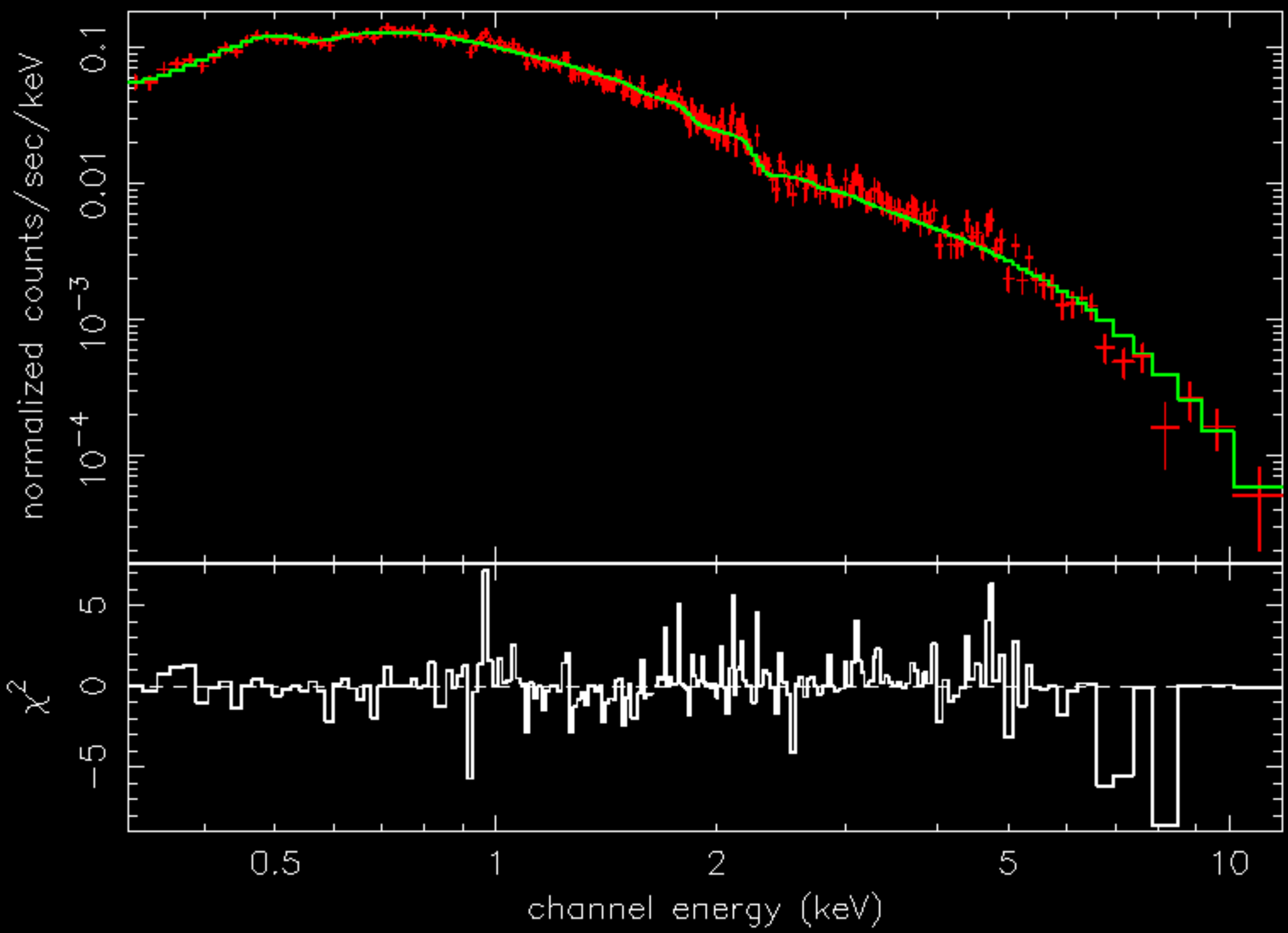


The obscuration of the opt. thick Comptonized emission region by a clumpy wind creates large-scale variability

X-ray spectrum of NGC4559 X7 (*XMM*)

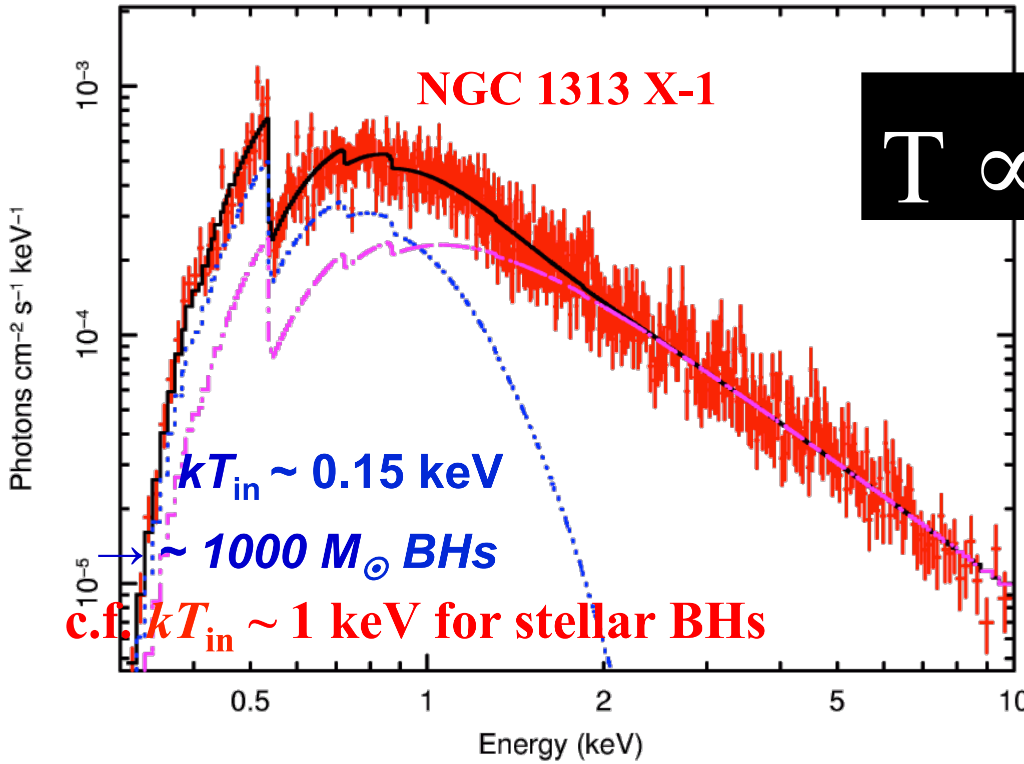


Thermal component at 0.12 keV = disk emission?



Cool disk temperature as indication of an IMBH? I

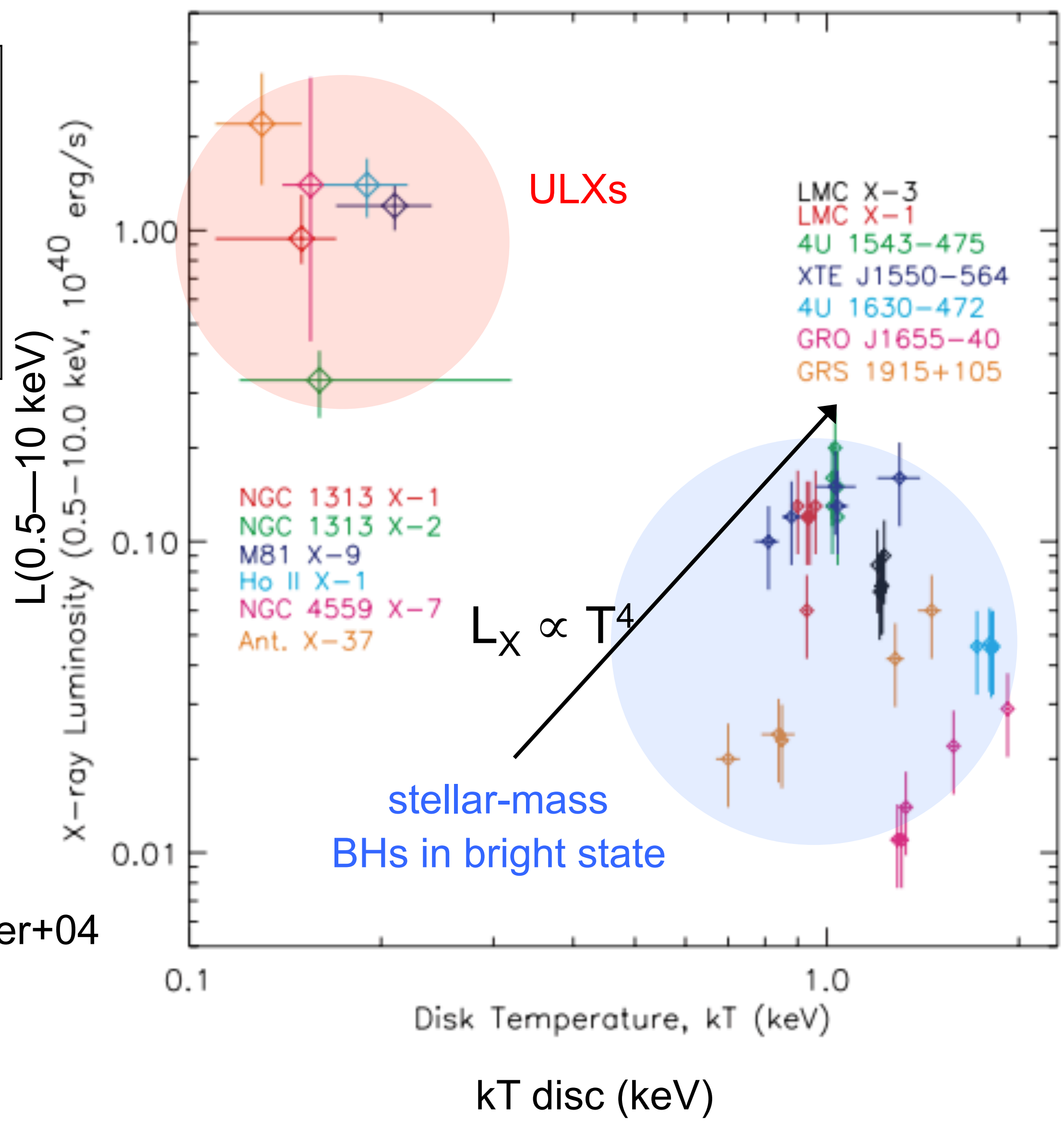
Needs further indications to support this hypothesis



$T \propto M^{-0.25}$

Cool disk temperature as indication of an IMBH? II

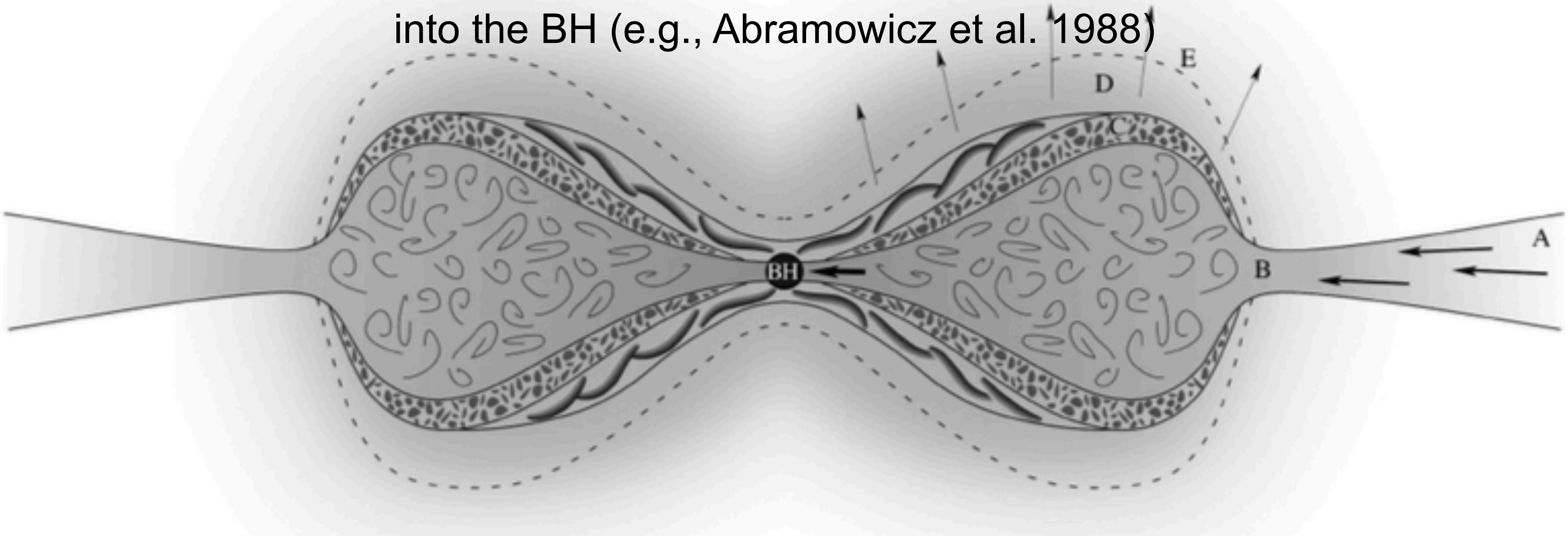
ULXs are brighter than stellar-mass BHs and have cooler disks



Miller+04

Slim disks
(allow to maximize the growth rate)

At high accretion rates, the disk becomes radiation pressure-dominated and 'slim' or 'thick' (scale height H≥r=radius) and advects the accretion energy with the flow. Inflow time for material in the disk < diffusion time for photons to reach the last scattering surface of the disk and radiate away ➔ Photons are trapped in the disk and advected into the BH (e.g., Abramowicz et al. 1988)



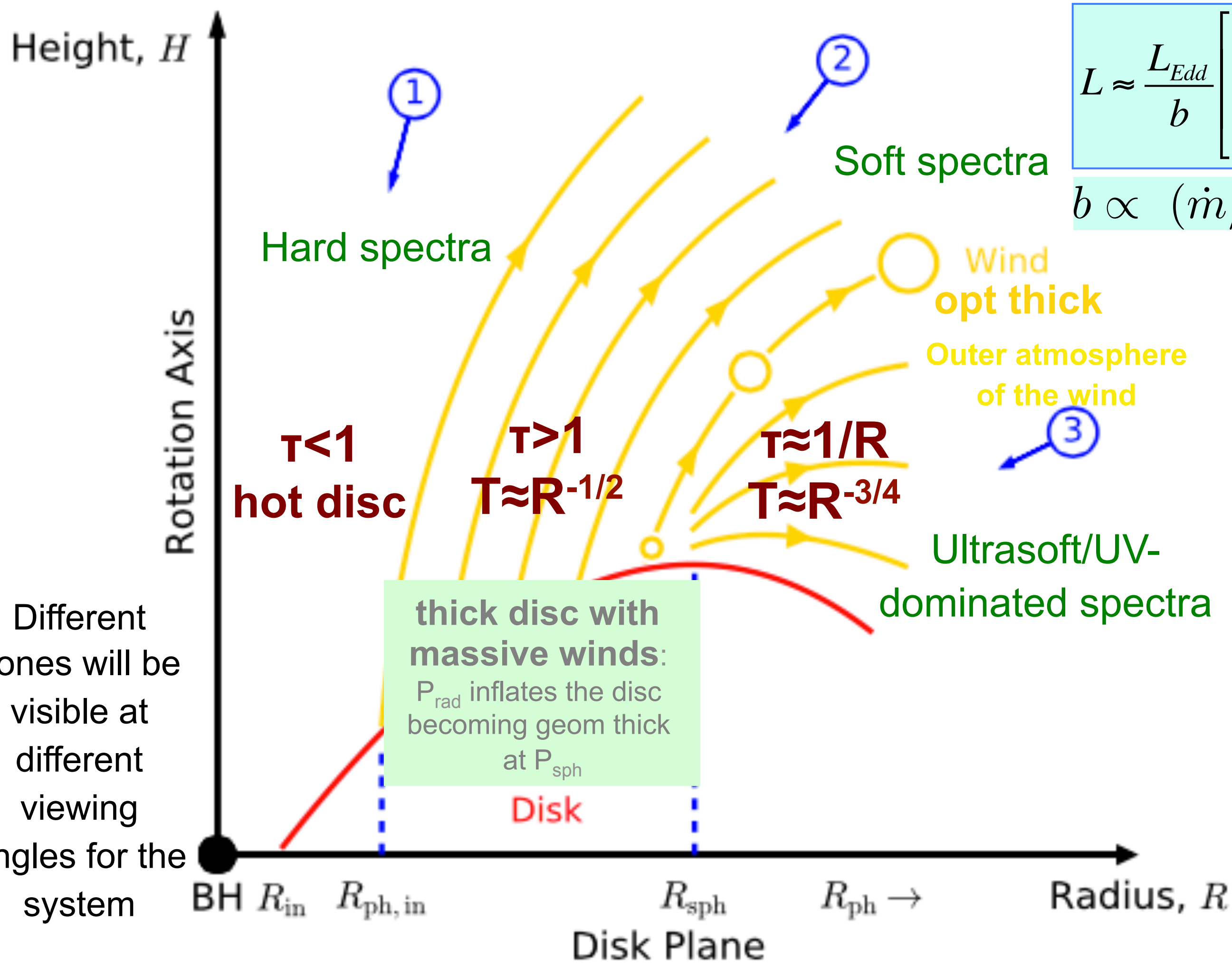
Dotan & Shaviv 2011

Central regions of the accretion flow: opt. and geom. thick
Low radiative efficiencies

- As L→Ledd, radiation pressure dominates and the disk becomes geometrically 'slim'
- As the scale height increases, advection becomes important, resulting in a broader, less peaked disk spectrum

Supercritical accretion flow. I

Super-Eddington accretion: the Eddington limit always applies locally, thus 'excess' material will be driven from the disk in the form of a massive wind



Different zones will be visible at different viewing angles for the system

$$L \approx \frac{L_{Edd}}{b}\left[1+\ln\left(\frac{\dot{m}}{\dot{m}_{Edd}}\right)\right]$$ - b: beaming factor

$$b \propto \left(\dot{m}/\dot{m}_{\rm Edd}\right)^{-2}$$

King 2008, 2009

The disk becomes geometrically thick at R_{sph} (spherization radius).

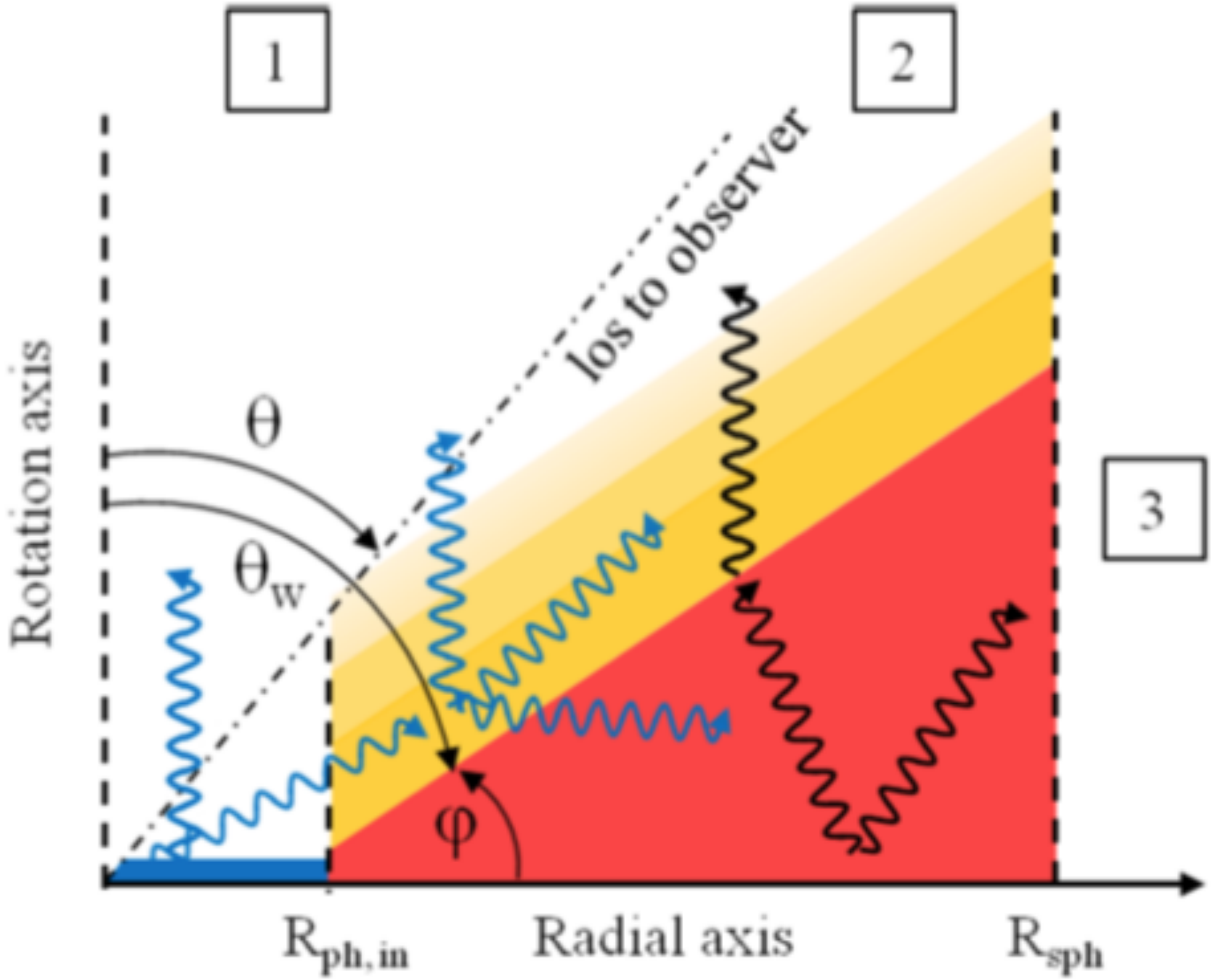
Within this radius, an optically thick outflow is blown away from the top of the disk by radiation pressure, which persists down to $R_{ph,in}$

$$R_{sph} = (\dot{m}/\dot{m}_{Edd})R_{in}$$

Kaaret+17 review, see also Middleton+15 and Poutanen+07; orig: Shakura & Sunyaev 1973

$R_{ph,in}$=inner edge of the photosphere (opt. depth=1)
R_{ph}=outer edge of the photosphere (opt. depth=1)

Supercritical accretion flow. II



Middleton+15

The scattering probability is large → depending on inclination angle, we may expect geometrical beaming to amplify the hard emission (e.g., King 2009, Poutanen+07) or scattered emission out of the line of sight
→ Variability can be present due to wind inhomogeneities (hence, obscuration + scattering effects)

Super-critical accretion and escape velocity

$$\dot{m} > \dot{m}_{crit} = (9/4)\dot{m}_{Edd}$$

$$v_{esc} > \sqrt{2GM_{BH}/R}$$

At $R=R_{sph}$ the scale height of the disc (H/R) exceeds 1

MAIN UNSOLVED ISSUE: ISOTROPIC OR BEAMED EMISSION?

Beamed emission?

Beaming: from jet (e.g., micro-blazar)? From geometry (e.g., accretion disc)?

- ❑ Mild geometrical beaming (structure in the accretion disc limiting the escape of photons, emerging preferentially in the directions of the lowest scattering optical depth, i.e. the poles)? If so, ULXs=HMXBs

- ❑ Relativistic beaming (i.e., jet)? If so, ULXs=microblazars

- ❑ No beaming? What we observe is the total intrinsic emission

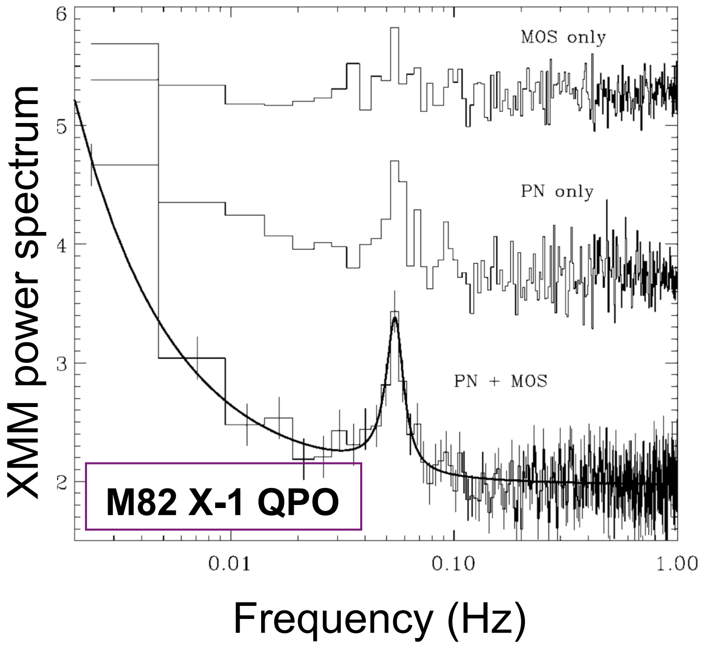
Against beamed emission

- ❑ Detection of QPOs and iron Kα line

- ❑ Presence of extended (hundred pc) emission nebulae

- ❑ Presence of eclipses

Indications against beamed emission

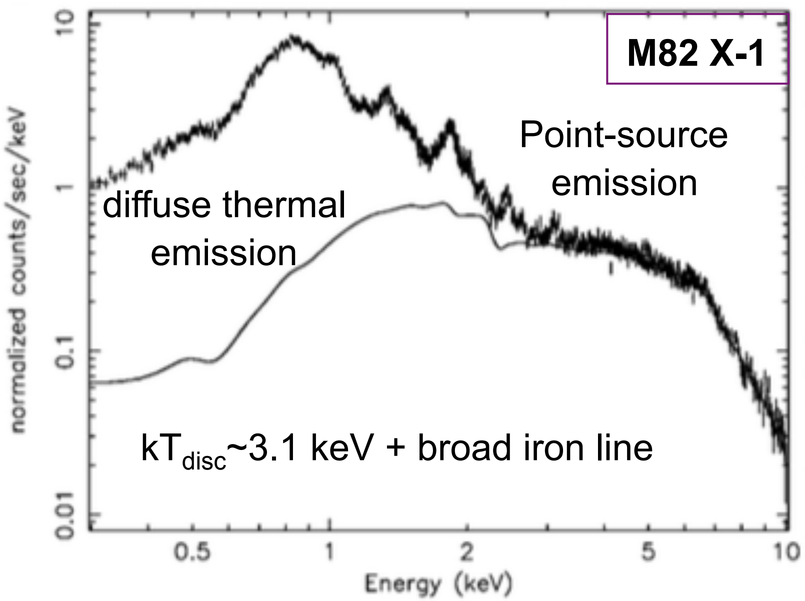


$R_{source} < c/\nu_{QPO} = 2.8\times10^6$ km. If ν_{QPO}=Keplerian frequency at the ISCO around a Schwarzschil BH, $M_{BH} < 1.9\times10^4\ M_\odot$

Geometrically thin disk likely. Thick disks would make (via scatterings) the QPO profile broader (similarly for its variability behavior)

Strohmayer & Mushotzky 2003

QPO ←→ disc



EW(FeKα)≈100 eV hard to explain if due to interaction of the jet with high-density cold material in polar direction (perpendicular to the AD)

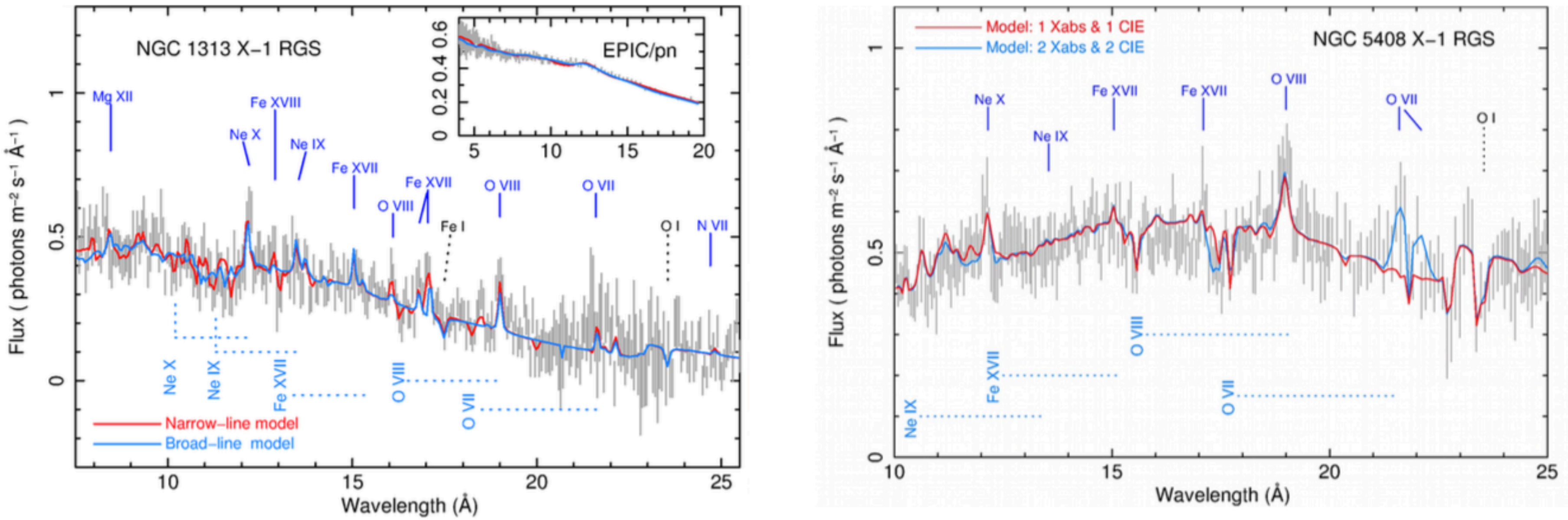
Beamed (blazar-like) sources do not show Fe K lines

OUTFLOWS

Outflows

i. Theoretical arguments (supercritical disks)
ii. MHD simulations
iii. Blueshifted lines in X-ray spectra
iv. High-velocity optical lines

Pinto+16, X-ray grating spectra, Nature



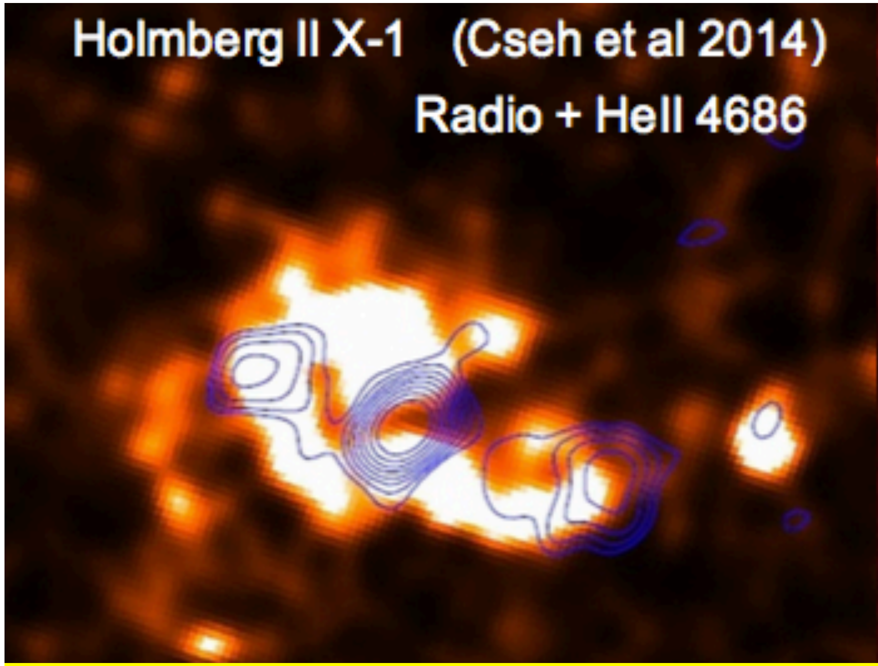
Model: isothermal emission model of gas in collisional ionization equilibrium.
V_{out}≈0.2c (NGC 1313 X-1) and V_{out}≈0.1c+0.22c (NGC 5408 X-1)

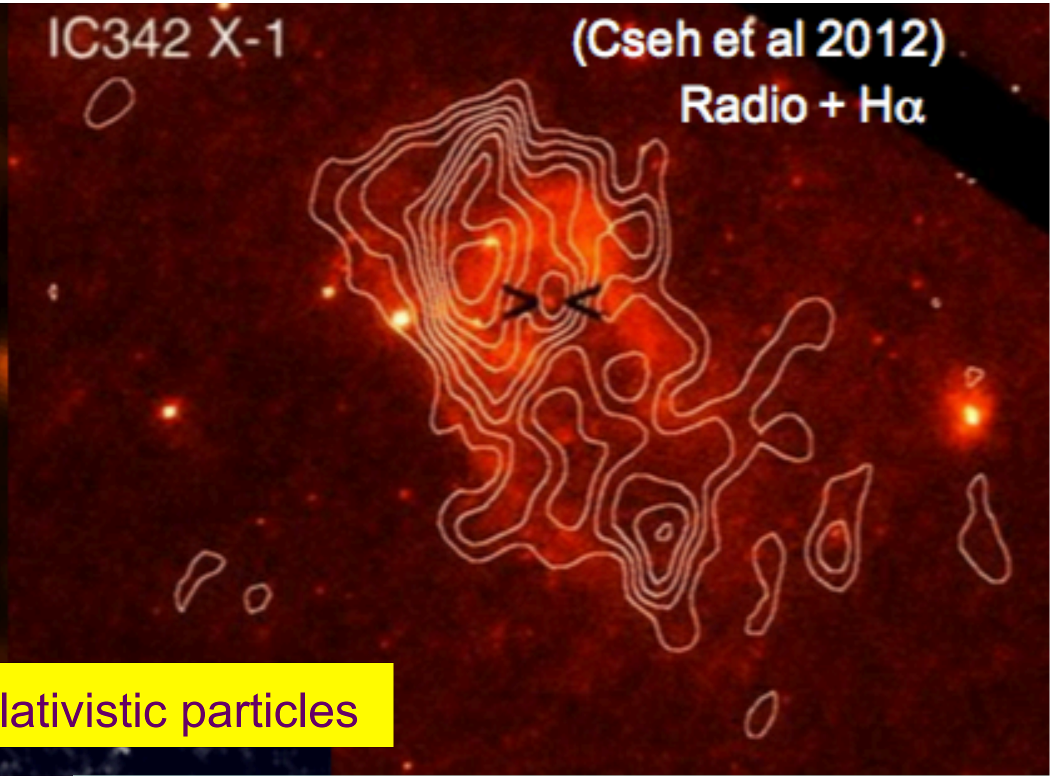
BUBBLES

ULX bubbles

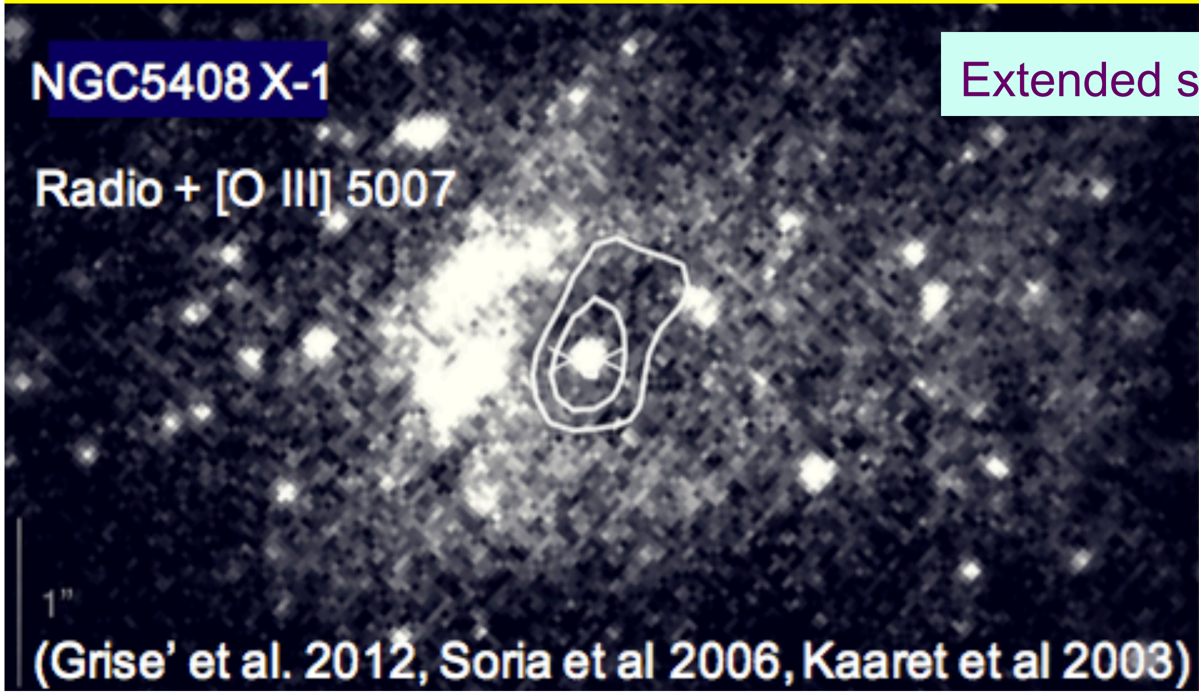
Some ULXs are coincident with optical nebulae (ten to hundreds of pc extension).
→ Shocks created by outflows from the binary interacting with the surrounding medium; in a few cases, the nebulae are powered by photoionization (Pakull & Mirioni 2003)
In both cases, L_{photo} (L_{mech})>10^{39} erg/s

Bubbles characterized by optical/UV emission lines (Hα, HeII, [OIII]) and, sometimes, synchrotron radio emission





A few percent of the total energy is in relativistic particles



Extended structures at various wavelengths

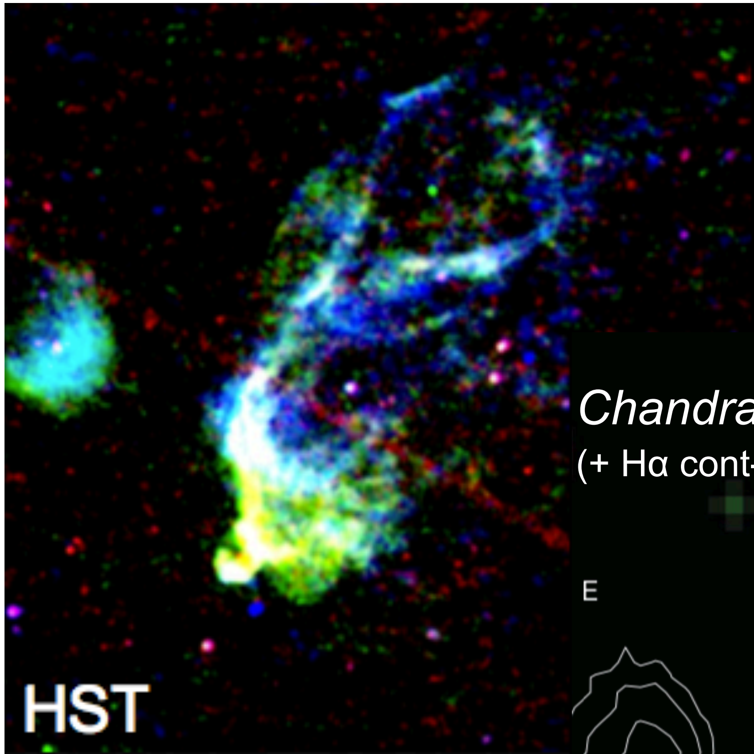
Indirect evidence of jets from optically-thin synchrotron emission

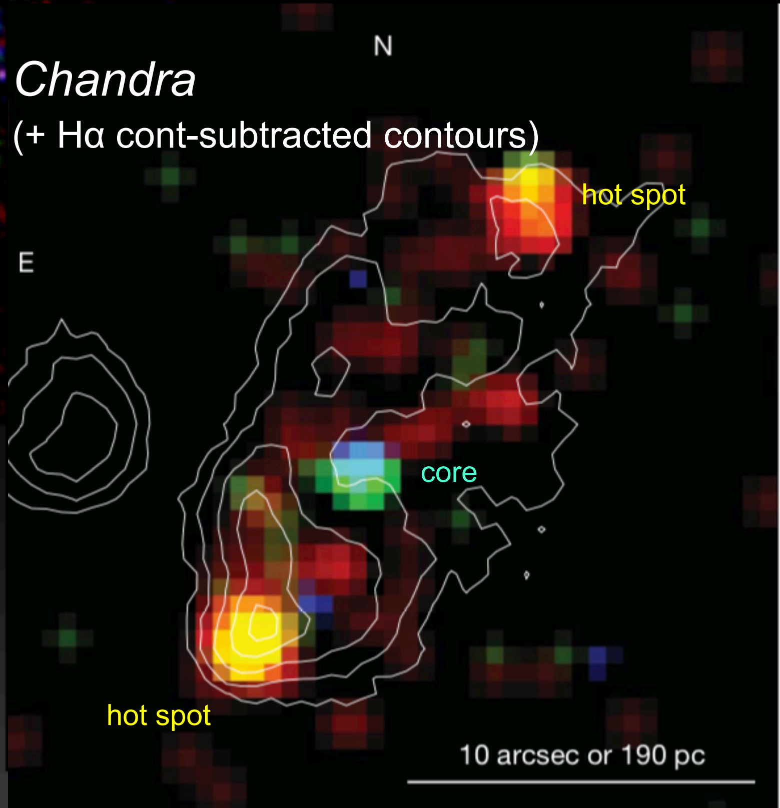
$P_{jet} \sim$ a few 10^{39} erg/s

inferred from the radio emission

S26 microquasar in NGC7793

(Pakull, Soria & Motch 2010)
(Soria et al 2010)



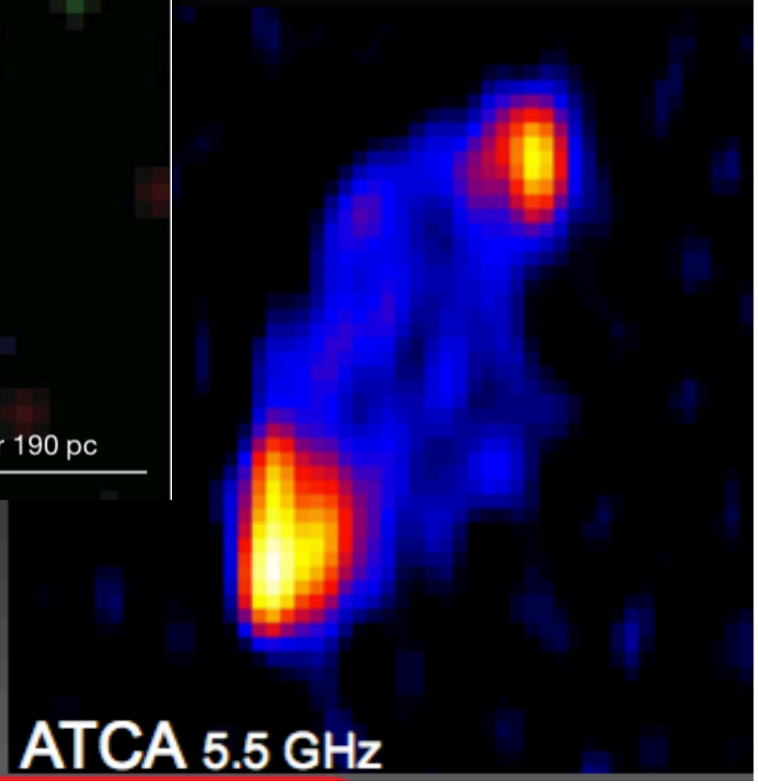


Jet with hot spots

$P_{jet} \sim$ 1E40 erg/s

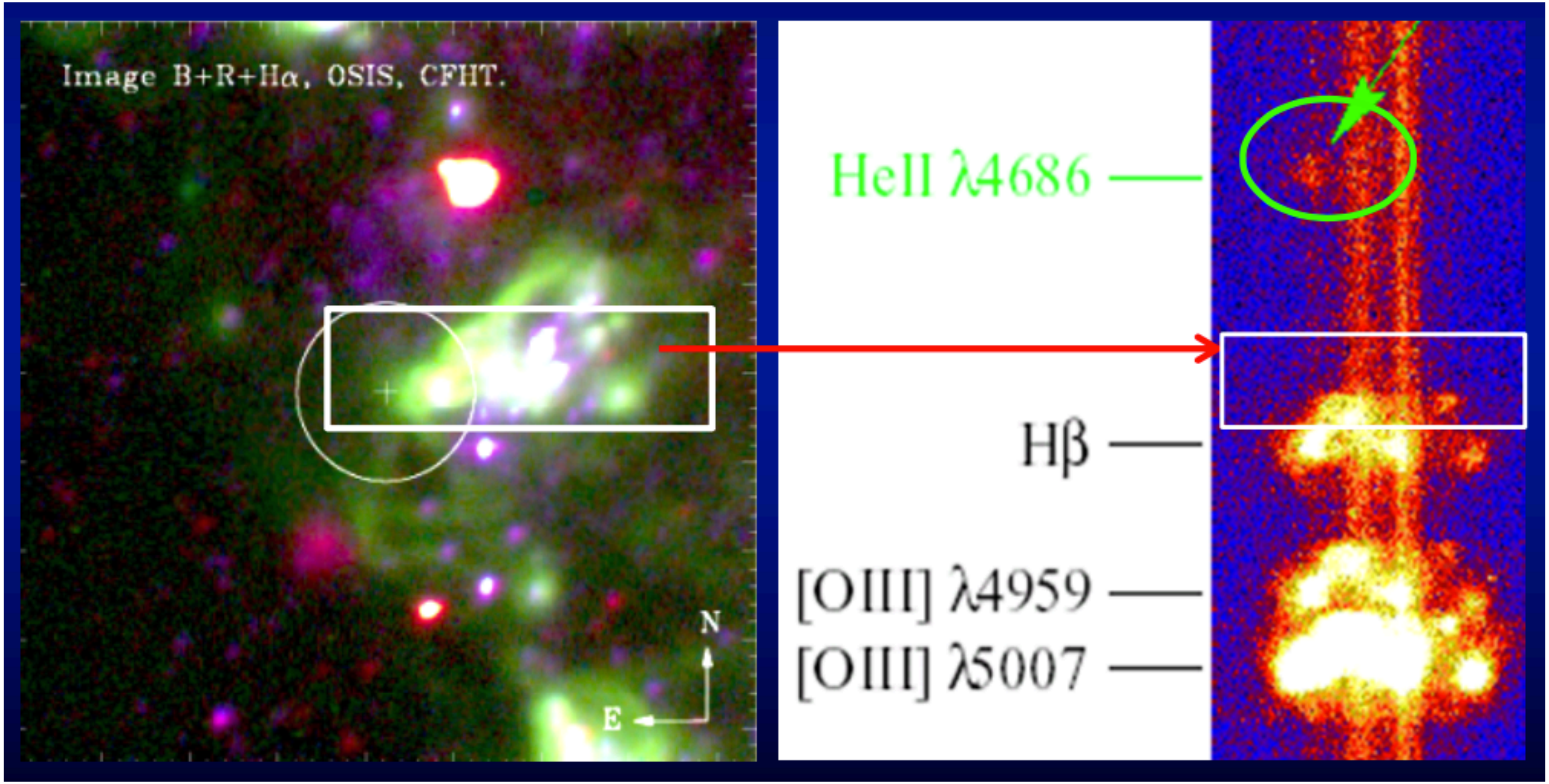
$L_X \sim$ 1E37 erg/s

ULX probably occulted (seen edge-on)



Holmberg II-X1: an X-ray photoionized nebula

HeII: recombination line with 54 eV ionization potential (close to the accreting object?)



$L_{HeII} \approx 2.5 \times 10^{36}$ erg/s
Integrated X-ray luminosity of $\approx 6 \times 10^{39}$ erg/s

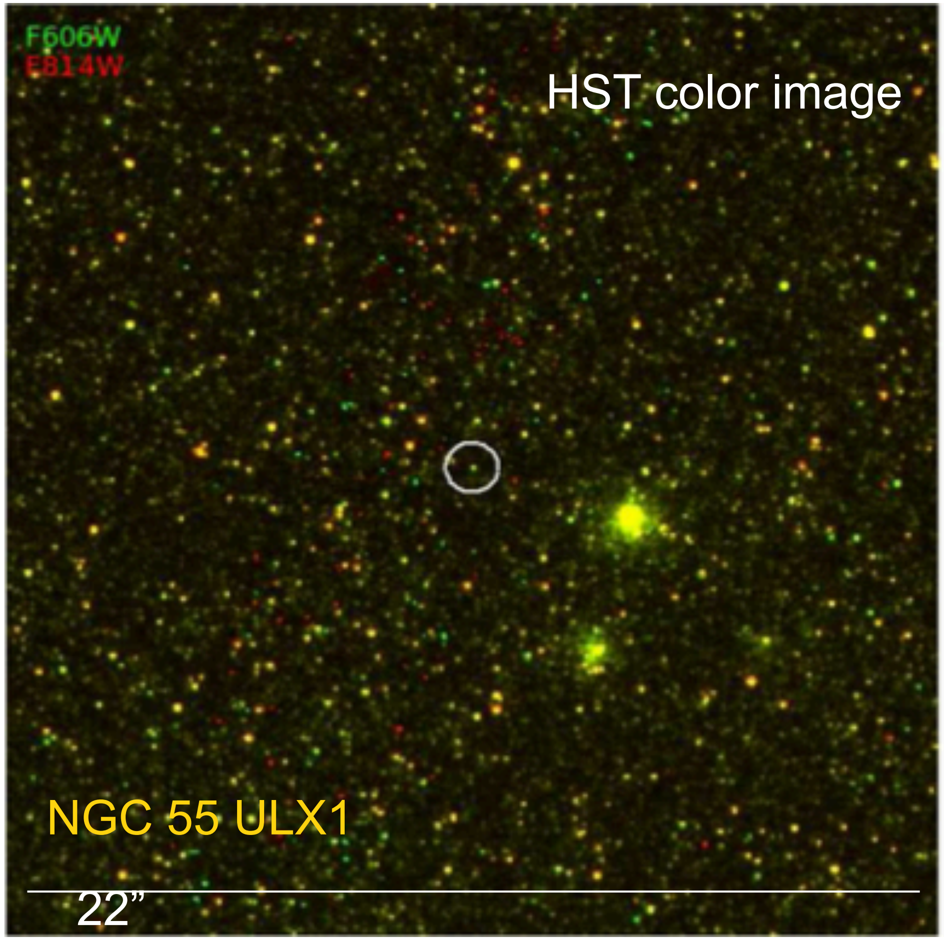
No sharp Strömgren sphere expected because gas becomes optically thin for high-energy photons. Outer region of warm, nearly neutral gas

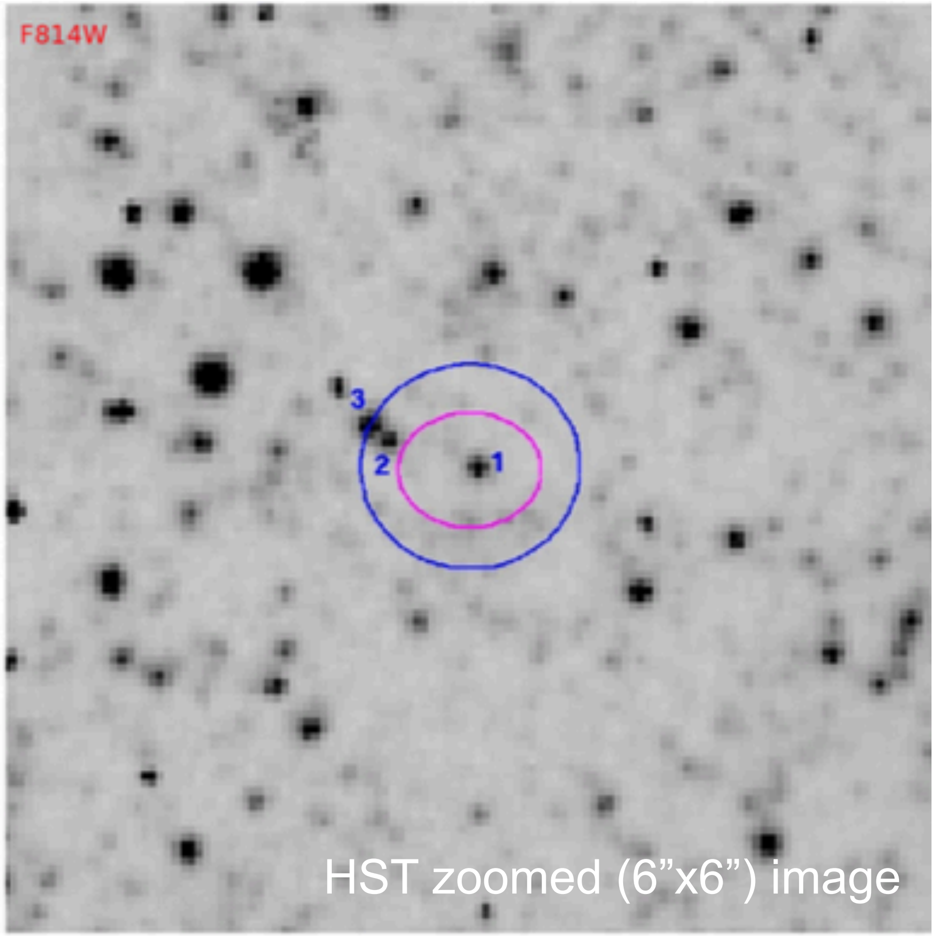
OPTICAL COUNTERPARTS

Radial velocity curves for the companion (hence constraints on the mass of the compact object via the mass function)

Sparse data and contamination from other emission preclude a definitive answer in most cases

High spatial-resolution imaging



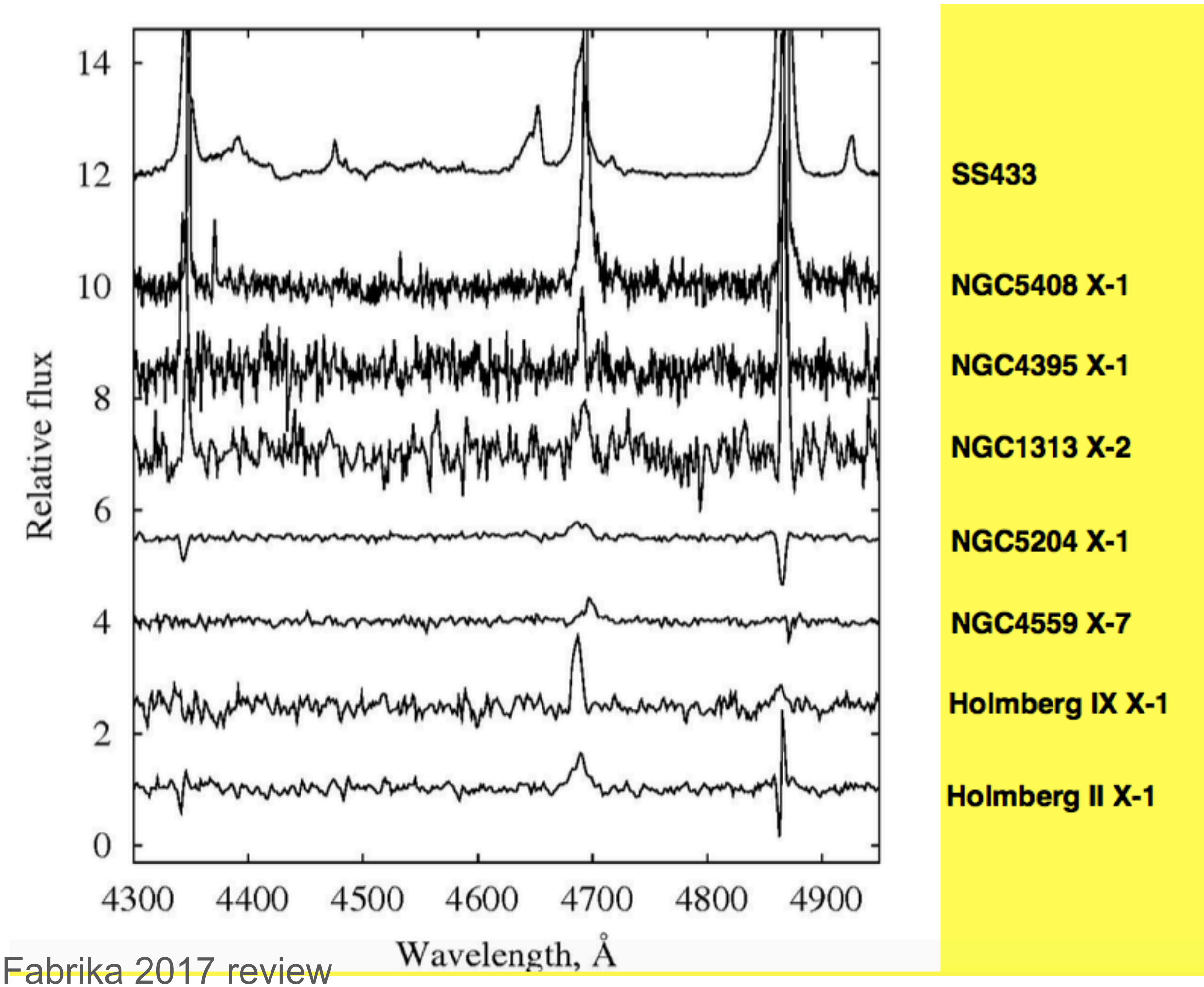


Gladstone+14

Search for the companion after careful astrometric corrections and using good spatial resolution images (*HST*, *Chandra*)
In this work, most counterparts are not O-type stars

Optical spectra of ULXs. I

- Helium lines + Hα + Hβ often present, optical signatures of massive outflows
- Some contamination from the nebulae. Some have stellar emission enhanced by emission from an irradiated star and/or accretion disk



Fabrika 2017 review

Similarities with SS433, a super-critically accreting BHC in the Galaxy

Spectra resembling those of WNL stars (late nitrogen Wolf-Rayet stars) or LBV (luminous blue variables) in their hot state, which are very scarce stellar objects

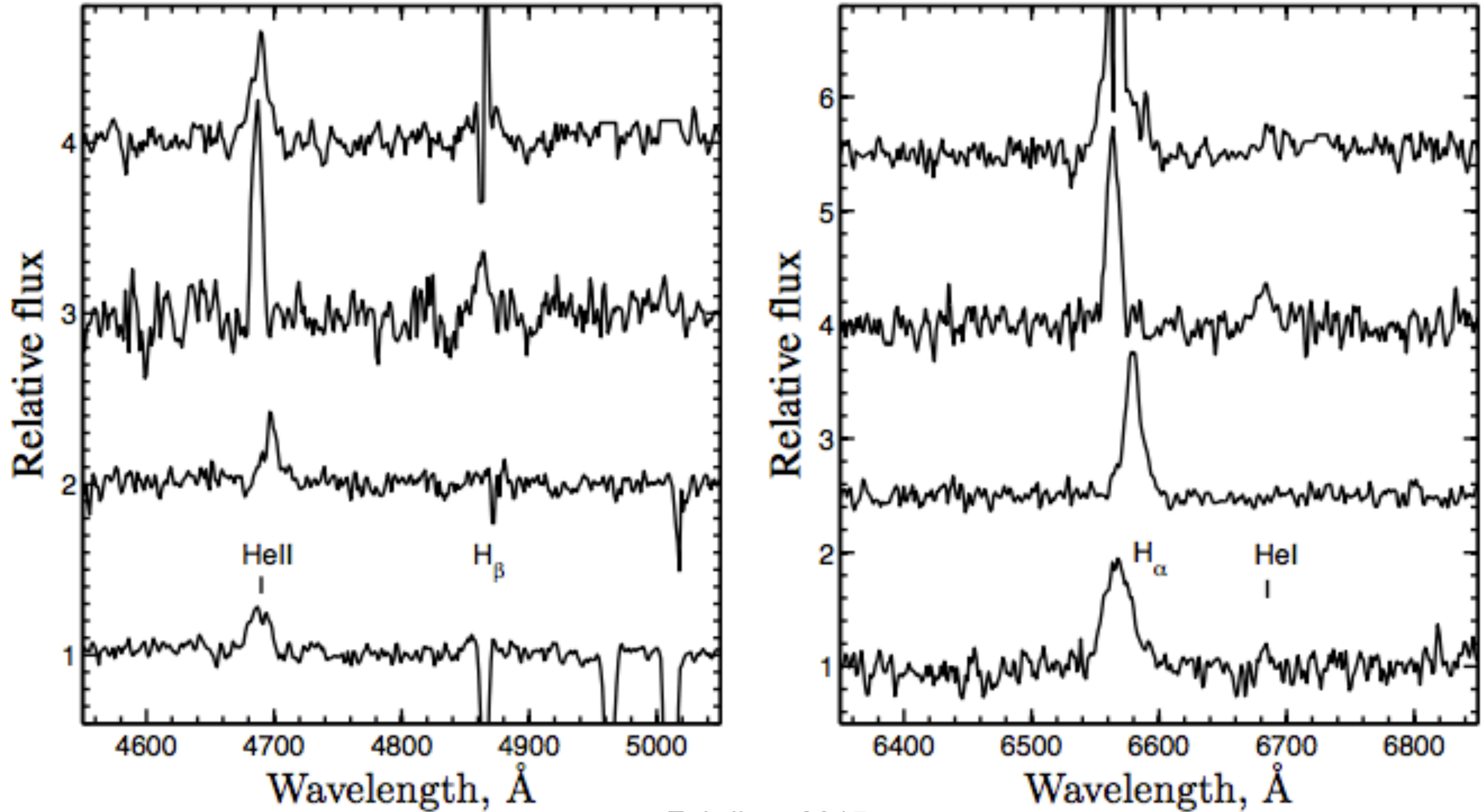
Blue (and sometimes red) supergiants counterparts (Tao+11, Gladstone+13)

Unusually high He/H

FWHM (HeII, often double-peaked, Hα) up to ≈1500 km/s, v(radial) up to ~800 km/s

Optical spectra of ULXs. II

Some optical (HeII, Hα) broad lines may be explained in the context of a radiatively accelerated wind (Fabrika+15)



Fabrika+ 2015

Are we looking at the base of the wind from the disk?

Evidence for strong outflows in ULXs:

Shock-powered optical and radio giant bubbles

Broad optical emission lines with relatively high v_{rad}

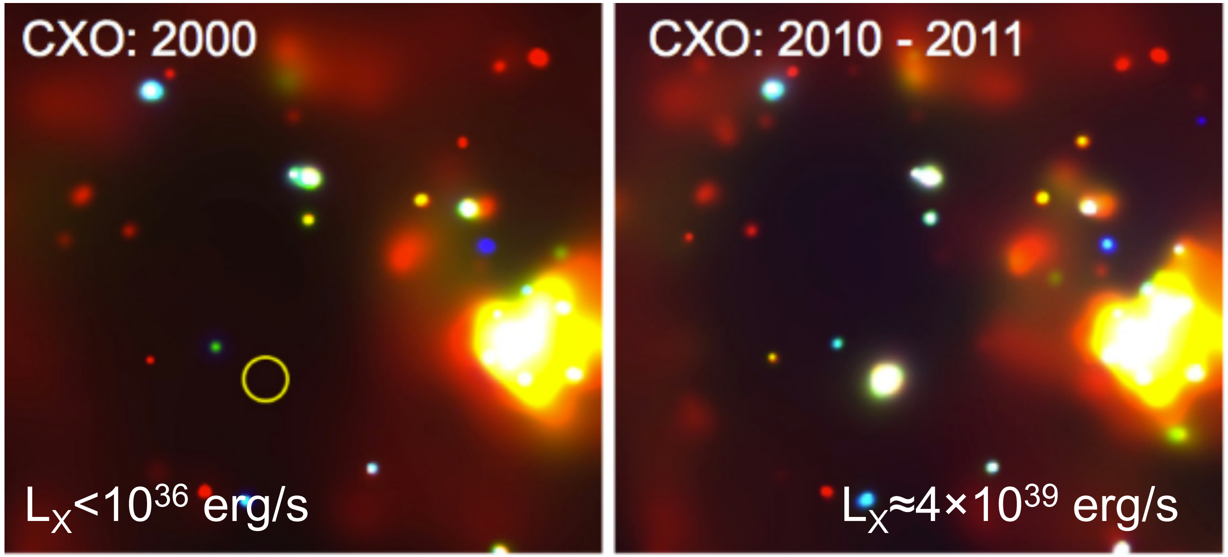
Blueshifted X-ray absorption lines

↓

Often $E_{kin}>E_{X\text{-}ray}$ ➔ a significant fraction of the total energy release of the accretion flow goes into powering an outflow

TRANSIENT ULXS

The birth of an ULX in M83

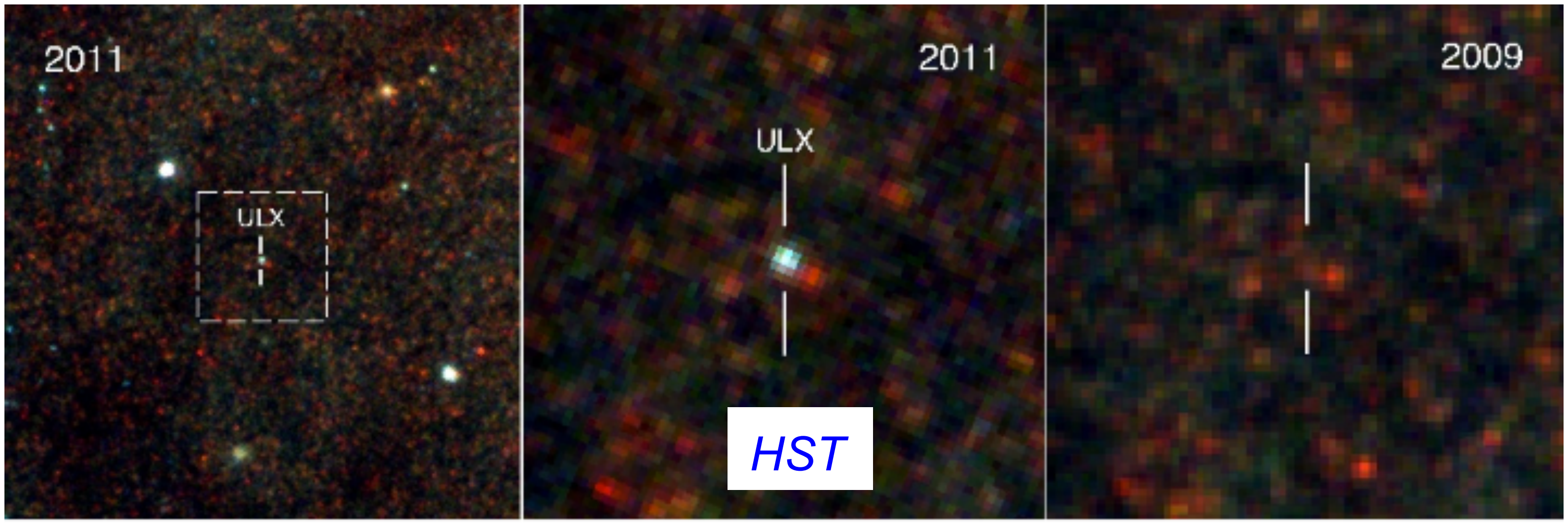


Soria+12

Chandra

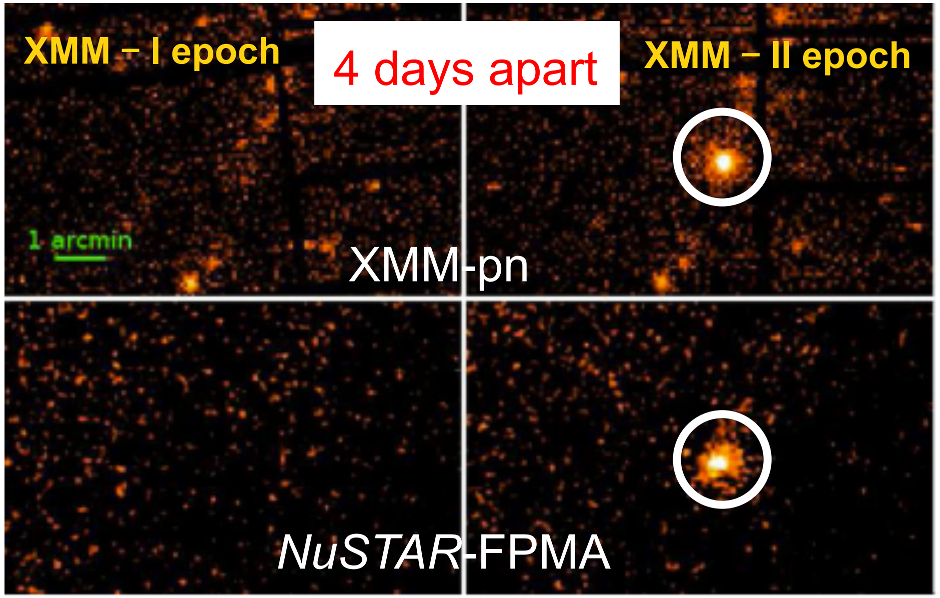
from X-ray spectrum (disc model) → R_{in} → $M_{BH} \approx 40-100\ M_\odot$

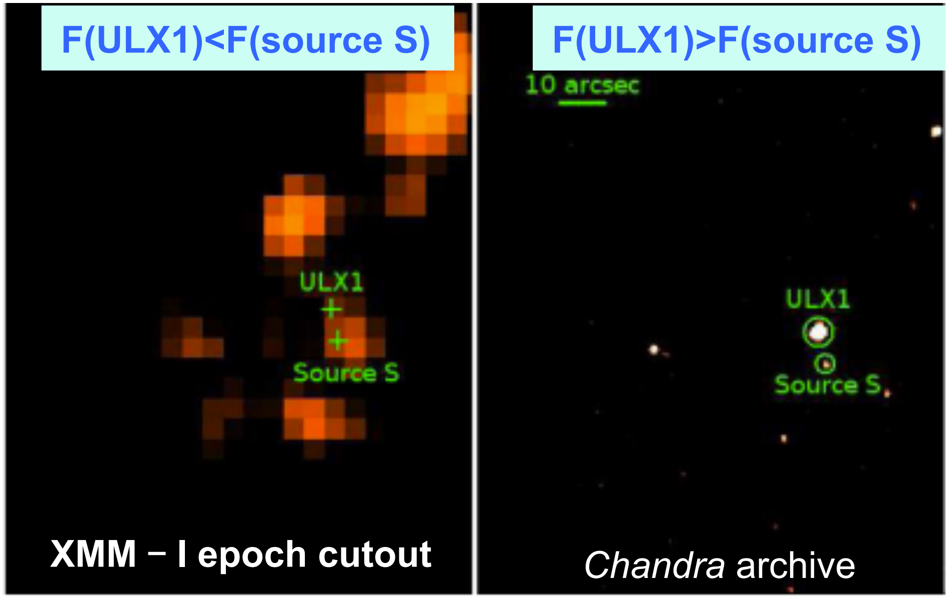
Low-mass donor ←→transient BH



Donor star: low-mass star undergoing Roche lobe overflow. The blue optical emission seen during the outburst is coming from an irradiated accretion disk

NGC 5907 ULX1: a vanishing act. I





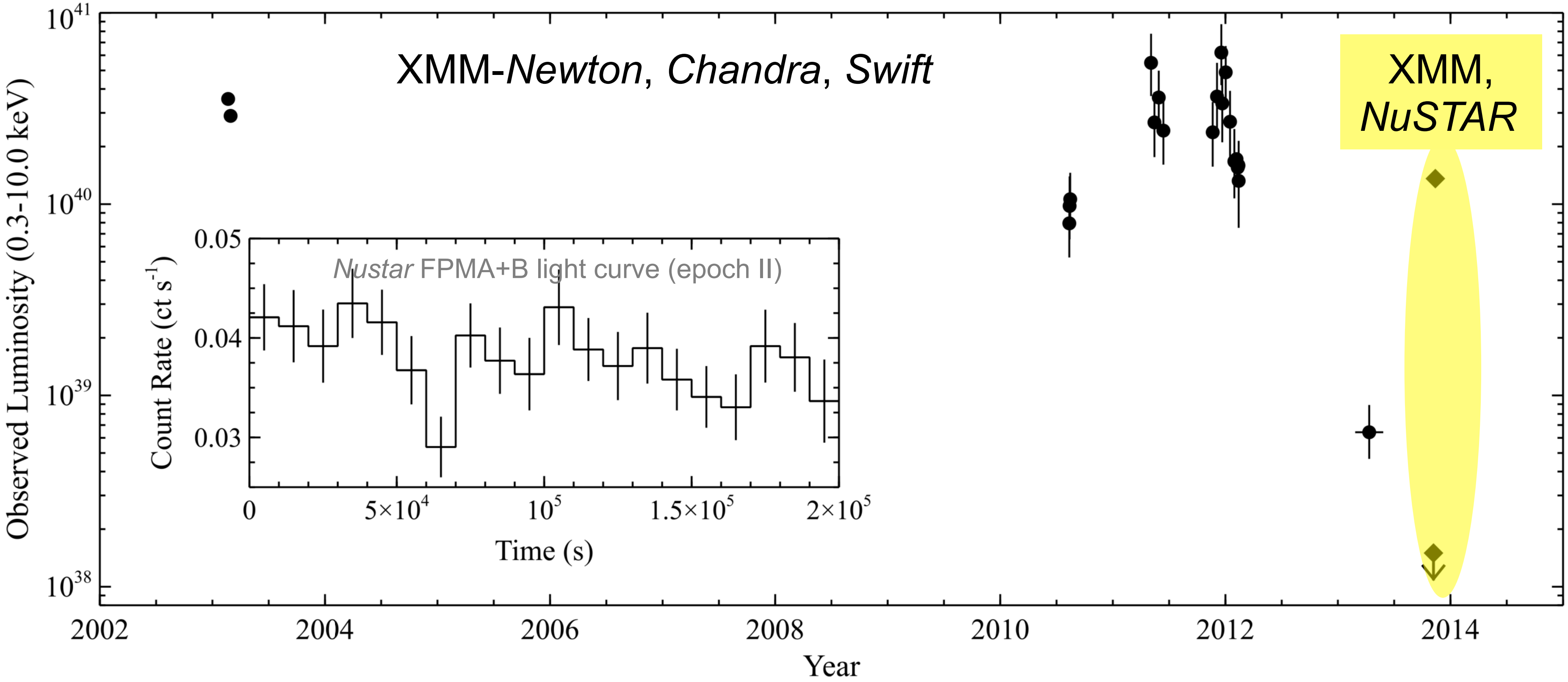
Walton+15

2 orders of magnitude increase in 4 day, likely due to an increase in the accretion rate
$L_{0.3-20\ keV} \approx 10^{40}$ erg/s

High-Eddington accretor in the high state?

Hints of older environment and no ULX bubbles in transient ULXs
Disk instabilities? Mass transfer instabilities? Still many unanswered questions & issues

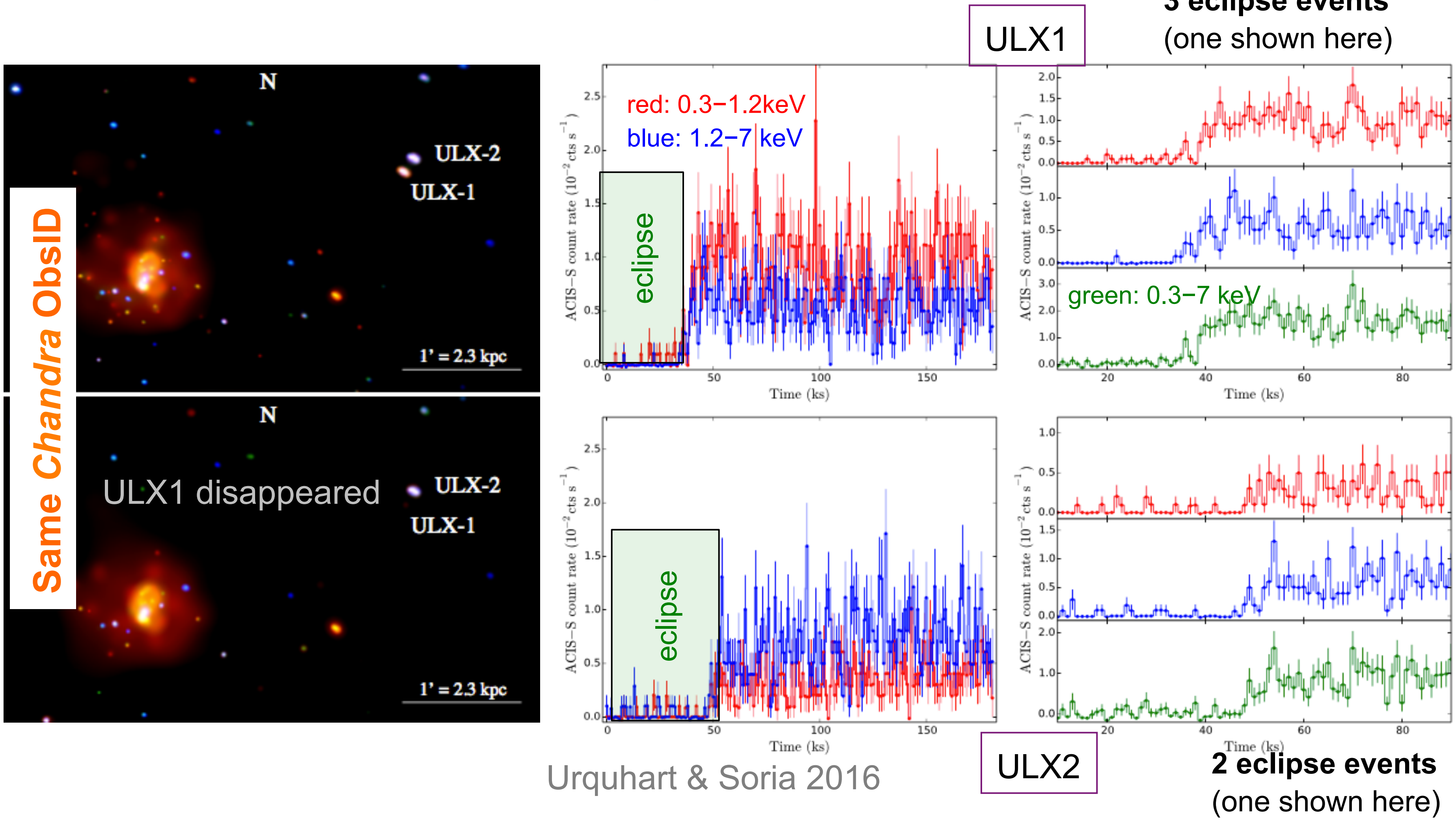
NGC 5907 ULX1: a vanishing act. II



Walton+15

PECULIAR DISCOVERIES ON ULXS

Eclipses in ULX



Urquhart & Soria 2016

- ULXs observed edge-on (hence, supporting the not-beamed hypothesis)
- ~10% flux visible during eclipses → emitting gas from a region more extended than the donor

DIFFERENT PROPERTIES, BOTH LIKELY ECLIPSED BY EVOLVED DONOR STAR

❑ ULX1 in SUL regime & radio jet, optical nebula like SS433

❑ ULX2 in BD regime (slim disc?) & bubble nebula?